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The effects of renewable diesels on the performance and exhaust emissions of a non-road diesel engine

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ABSTRACT:
Diesel engines are popular because of their high efficiency, durability, reliability and low-operating costs. However, they still may pollute the environment despite of good qualities of liquid fuels. Nitrogen oxides and particulate matter emissions are the most critical emissions from diesel engines.

The aim of this thesis was to examine the effects of renewable diesels and renewable diesel blend on the performance and emissions of a non-road diesel engine. Two renewable wood-based diesel fuels and one renewable diesel fuel blend were studied in a non-road engine. Fossil diesel fuel was used as the reference fuel. The test engine was a turbocharged, intercooled non-road diesel engine which had a common rail fuel injection system and no exhaust aftertreatment system. Nitrogen oxides, carbon monoxide, hydrocarbons, carbon dioxide and particle number emissions were measured in laboratory conditions. The measurements were conducted using the load points of the eight-mode non-road test cycle of the ISO 8178 standard.

In terms of nitrogen oxides, carbon monoxide, hydrocarbons and particle number, reductions were detected with both renewable fuels and the fuel blend compared to fossil diesel fuel over the test cycle. The highest reductions were in particulate emission, between 10–26%. Carbon monoxide emissions reduced by 2–9% and hydrocarbon emissions by 6–12%. In terms of nitrogen oxides, the highest reduction was 9% but otherwise reductions were quite low. Reasons for detected reductions in emissions were probably due to the high cetane number, low viscosity, low distillation range and low sulphur and aromatic content of renewable diesels and blend.

KEYWORDS: diesel engine, non-road, renewable diesel, CTO, HVO, exhaust gas, nitrogen oxides, carbon monoxide, hydrocarbons, particulate number

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TIIVISTELMÄ:
Dieselmoottorit ovat suosittuja niiden korkean hyötysuhteen, kestävyyden, luotettavuuden sekä alhaisten käyttökustannusten vuoksi. Hyvistä ominaisuuksista huolimatta dieselmoottorit ovat yksi merkittävä päästölähde. Erityisesti typen oksidit ja pienhiukkaset ovat dieselmoottoreissa ongelmallisia.

Tämän diplomityön tavoitteena oli selvittää uusiutuvien dieselpolttoaineiden vaikutus työkonedieselmoottorin suoritusarvoihin ja pakokaasupäästöihin. Tutkittavana oli kaksi puuperäistä uusiutuvaa dieseliä ja yksi uusiutuvan ja fossiilisin dieselin seos. Fossiilista dieselpolttoainetta käytettiin verrokkipolttoaineena. Koemoottorina käytettiin turboahdettua työkonedieselmoottoria ilman pakokaasun jälkikäsittelyä. Tutkimuksessa moottorin pakokaasusta mitattiin typen oksidit, hiilimonoksidi, hiilivedyt, hiilidioksidi sekä pienhiukkasten lukumäärä.

Tutkimuksessa havaittiin päästöjen väheneminen uusiutuvilla polttoaineilla ja seoksella typen oksidien, pienhiukkasten, hiilimonoksidin ja hiilivetyjen osalta. Hiukkaspäästöt vähenivät tutkimuksessa eniten, 10–26%. Hiilimonoksidipäästöt vähenivät 2–9% ja hiilivetypäästöt 6–12%. Typen oksidien päästöt alenivat enimmillään 9%. Hiilidioksidipäästöt olivat suunnilleen samat uusiutuvilla polttoaineilla kuin fossiilisella dieselillä. Pakokaasupäästöjen väheneminen johtui todennäköisesti uusiutuvien polttoaineiden ja seoksen korkeasta setaaniluvusta, pienestä viskositeetista, alhaisesta tislausalueesta sekä polttoaineiden vähäisestä sulfaatin ja aromaattisten hiilivetyjen määrästä.

AVAINSANAT: dieselmoottori, uusiutuva diesel, CTO, HVO, pakokaasu, typen oksidit, hiilimonoksidi, hiilivedyt, pienhiukkaset

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Abbreviations

CO	Carbon Monoxide
CO_2	Carbon Dioxide
CTO	Crude Tall Oil
DFO	Diesel Fuel Oil
EU	European Union
FAME	Fatty Acid Methyl Ester
FT	Fischer-Tropsch
FTIR	Fourier Transform Infrared
H_2O	Water
HC	Hydrocarbon
HVO	Hydrotreated Vegetable Oil
NMHC	Nonmethane Hydrocarbons
NO_x	Nitrogen Oxides
NO_2	Nitrogen dioxide
NRSC	Non-road Steady Cycle
PAH	Polynuclear Aromatic Hydrocarbons
PM	Particulate Matter
PN	Particle Number
RME	Rapeseed Methyl Ester
THC	Total Hydrocarbons

1 Introduction

Decreasing crude oil reserves and increasing concerns about climate, environment and human health has forced us to find alternative solutions for fossil fuels. New fuels should emit low levels of exhaust gas emissions, meet the sustainably criteria and be suitable for existing infrastructure and internal combustion engines as well.

The European Union´s (EU) main climate and energy goals for 2030 are cutting at least 40% greenhouse gas emissions from 1990 levels, increase share of renewable energy to 27% and make at least 27% improvement in energy efficiency. Even though actions are mostly driven by need to decrease greenhouse gas emissions, the need to decrease sulphur, nitrogen oxides (NO_x) and particulate matter (PM) emission is also high. (Bauen et al., 2018, pp. 3, 7.)

Diesel engines are popular especially in heavy-duty vehicles because of their high efficiency, durability, reliability and low-operating costs. However, they still may pollute the environment despite of good qualities of liquid fuels. (Reşitoğlu et al., 2014, p.15.) Especially NO_x and PM emissions are the most critical emissions from diesel engines.

In particular, transport sector is highly dependent on oil since it has high energy density, existing infrastructure and lower cost compared to other alternatives (Bauen et al., 2018, p. 3). Emissions from diesel engines can be decreased by replacing fossil fuels to renewable diesel fuels.

FAME (Fatty Acid Methyl Ester) fuels are the widely produced alternative to fossil diesel. They are made via transesterification of vegetable or animal oils. Problem with FAME is that oils are mostly derived from farm-based feedstock and compete with food production. Nowadays interest is increasingly focused on the renewable diesels which use waste biomass, algae or other non-food cellulosic material as a feedstock. These renewable diesels are composed of paraffinic hydrocarbons and they are made either via hydrotreatment or Fischer-Tropsch (FT) process. (Bhardwaj et al., 2013, pp. 157-158.)

Hydrotreated vegetable oil (HVO) can be derived from different vegetable oils and fats. Tall oil, algae oils, residues and wastes are at the moment interesting choices since they do not compete with food production. (Douvartzides, 2019, pp. 812-813.) With HVO there is no need to modify the engine or existing fuel distribution infrastructure, so they could be used as direct replacement for fossil diesel in engines (Bauen et al., 2018, p. 24).

In Finland there is a high interest in wood based HVO which is produced from crude tall oil (CTO). CTO is a by-product from the production of pulp. In terms of the raw material availability, Finland has over 20 million hectares forest land (Luke, 2020) and pulp is produced there over 8 million tonnes in a year (Metsäteollisuus ry, 2020). The share of CTO production is approximately 30 kg per one tonne of pulp (Blom, 2020). HVO from CTO does not compete with food production and does not contribute net carbon dioxide (CO_2) in the atmosphere. (Douvartzides et al., 2019, p. 838).

This study aimed to examine the effects of renewable diesels and a renewable diesel blend on the performance and emissions of a non-road diesel engine. Two renewable diesel fuels and one renewable diesel fuel blend were studied in the test engine. Renewable diesels were derived from crude-tall oil (BVN, BVO) by hydrotreating. Fossil diesel fuel oil (DFO) was used as the reference fuel. The fuel blend was consisted of 50 vol.-% BVN and 50 vol.-% DFO. The measurements were conducted at eight load points which were selected according to the C1 driving cycle of the ISO 8178 standard. The C1 steady state cycle is known as the non-road steady cycle (NRSC).

The main emissions which were measured in this study were NO_x, carbon monoxide (CO), hydrocarbons (HC), CO_2 and particle number (PN).

This thesis consists of seven chapters. Chapter 1 is the introduction of the thesis. Chapter 2 focuses on diesel emissions, regulations and fuel standards. Chapter 3 concentrate on the HVO, HVO production from CTO and properties of HVO. Chapter 4 presents the experimental setup of the study. Chapter 5 shows the results. Chapter 6 provides the conclusions based on this study. Summary of the thesis is in Chapter 7.

2 Diesel emissions, regulations and fuel standards

In this chapter diesel fuel standards EN 590 and EN 14940, emission standard EU Stage V and the C1 cycle of ISO 8178-4 standard are shortly presented at first. The CI engine's main emission components and their formation is then described.

2.1 Emissions from CI engine

Diesel fuel is a mixture of hydrocarbons. Ideal combustion of hydrocarbons theoretically produces only CO_2 and water vapour (H_2O) during combustion. Produced water is harmless to the environment, but CO_2 contributes the greenhouse effect. Amount of produced H_2O and CO_2 during combustion is dependent from the H/C ratio of fuel. (Mollenhauer & Tschöke, 2010, p. 443.)

In reality, several non-ideal processes occur in combustion resulting in unwanted emissions. These processes include incomplete combustion of fuel, reactions between mixture components in high pressure and temperature, combustion of engine lubricating oils and fuel additives and combustion of non-hydrocarbon components such as sulphur. Diesel emissions can be toxic to humans or cause negative environmental effects. (Majewski & Khair 2006, p. 121.)

Regulated emission from diesel engine are NO_x, particle mass, PN, HC and CO. NO_x and PM are the most critical emissions from diesel engines while CO and HC emissions from diesel engines are quite low. (Majewski & Khair 2006, p. 121.)

2.1.1 NO_x

NO_x includes nitric oxide (NO) and nitrogen dioxide (NO_2). (Majewski & Khair 2006, p. 123.)

NO is colourless and odourless gas. It is formed by reaction between nitrogen and oxygen under a high temperature:

$$N_2 + O_2 = 2NO \quad (1)$$

When temperature and pressure increase in the cylinder, chemical equilibrium moves more to the right side of the equation (1) and more NO emission is formed. (Majewski & Khair 2006, p. 123.) The formation of NO occurs in local temperature peaks not mean temperatures in combustion chamber. Excess oxygen is also necessity for the NO formation. (Mollenhauer & Tschöke, 2010, p 445.)

NO_2 is highly toxic red-brown gas with irritating odour. Proportion of NO_2 in total NO_x emissions is approximately 5%. NO oxidize to NO_2 spontaneously at ambient conditions:

$$2NO + O_2 = 2NO_2 \quad (2)$$

(Majewski & Khair 2006, p. 123.)

NO_2 is extremely reactive and has strong oxidation properties (Majewski & Khair, 2006, p. 123). NO_2 is key precursor of range of secondary pollutants, such as organic, nitrate and sulphate particles, which effect on human health (World Health Organization, 2005, p. 331). NO_2 is also significant initiator of photochemical formation of ozone and acid rain. (Majewski & Khair, 2006, p.123; Sudalma, 2015, p. 248).

2.1.2 CO

CO is formed by incomplete combustion where oxidation does not occur completely (Reşitoğlu et al., 2015, p. 17). This can be either due to the lack of oxygen or low air-fuel mixing. CO correlates with air-fuel ratio and the oxygen content of the fuel. High oxygen content of the fuel and high air fuel ratio decrease CO emissions. (Vakkilainen, 2016, p. 50) Diesel engine operates always with excess air so the air fuel ratio of diesel engines is high which reduces CO emissions (Heywood, 2018, p. 157).

CO does not cause climate change directly but it affects the abundance of greenhouse gases such as methane (CH_4) and CO_2 in the atmosphere. CO also contributes the formation of ozone. (Voiland, 2015.)

2.1.3 HC

Most of the HC emissions results from incomplete combustion of the fuel. Part of the HC emissions are also derived from combustion of lubrication oil in the engine. (Prasad, 2014, p. 9). HCs are commonly regulated either as total hydrocarbons (THC) or nonmethane hydrocarbons (NMHC). NMHC excludes CH_4 because of its different atmospheric reactivity compared to the other hydrocarbons. In general, however, concentration of CH_4 is quite low in diesel engines. (Majewski & Khair 2006 p. 123.)

There are few major causes for HC formation in the engine. Most significant cause is too lean fuel-air mixture which disturbs combustion process in the engine. Fuel can also get trapped in the nozzle sac and enter combustion process late. Quenching, misfiring and over-fueling can be cause of HC emissions. (Prasad, 2014, p.9.)

When reaching into the atmosphere HC undergoes photochemical reactions with NO_x resulting smog and ground-level ozone. CH_4 does not react with NO_x but it is considered as a greenhouse gas. Some of the hydrocarbons can also be toxic or carcinogenic. (Majewski & Khair 2006 pp. 123-124.)

2.1.4 PM

Exhaust particulate matter (PM) is the most complex of exhaust emissions. Despite amount of research a full understanding of its physical and chemical properties, and its effect on human health and the environment is still lacking. PM is responsible for the black smoke from diesel engines. (Majewski & Jääskeläinen, 2019.)

PM can be divided into three main fractions which are solid fraction, soluble organic fraction and sulphate particulates. Major part of solid fraction is composed of elemental carbon which results from combustion process where solid particle precursors are formed in diffusion and premixed flame. Other part is composed from ash which consists of a mixture of sulphates, phosphates or oxide of calcium, zinc, magnesium and other metals. These are formed in the engine's combustion chamber from burning additives from lubricating oil. Some metal and iron oxides are also resulting from engine wear and corrosion of engine. (Majewski & Khair, 2006, pp. 127-129.)

Soluble organic fraction is derived from hydrocarbons mainly from lubricating oil but also from fuel. Formed hydrocarbons are mostly polynuclear aromatic hydrocarbons (PAHs) which have mutagenic and some cases carcinogenic properties. Part of the soluble organic fraction consist dioxins which are a group of chlorinated polynuclear hydrocarbon compounds. These are highly toxic, carcinogenic and resistance to biological breakdown. (Majewski & Khair, 2006, pp. 128-132.)

Sulphate particulates are composed mainly of hydrated sulphur acid which forms in reaction between sulphur dioxide and water. Sulphur dioxide is derived from the sulphur in the fuel. Sulphate particulates may also contain sulphur salts. (Majewski & Khair, 2006, pp. 128-133.)

PM is divided often into categories based on the aerodynamic diameter. PM_{10} includes particulates which have diameter less than 10 µm. $PM_{2.5}$ includes particles with diameter below 2.5 µm. Ultrafine particles diameter is less than 0.1 µm and nanoparticles less than 0.05 µm. (Majewski & Khair, 2006, p. 134.)

Particles can be also divided into three modes based on their size, nucleation mode, accumulation mode and coarse mode. Nucleation mode includes particles with diameter between 3 – 40 nm. It is mainly composed from hydrocarbons and hydrated sulphur acid

(depending the amount of sulphur in the fuel). Primary carbon particles can also be present. (Majewski & Jääskeläinen, 2019.)

Accumulation mode particulates have a diameter of between 40 nm – 1 µm. It consists of primary carbon particles which have agglomerated and absorbed other species and then formed structures with complex physical and chemical properties. (Majewski & Jääskeläinen, 2019.)

Coarse mode includes the particles which have diameter above 1 µm. These particles are formed from through deposition and subsequent re-entrainment of particulate material from walls of the engine cylinder, exhaust system or particulate sampling system, not from the combustion process itself. (Majewski & Khair, 2006, p. 135.)

In terms of number, particle size distribution has usually bimodal shape with two peaks, nucleation mode peak and accumulation mode peak. Nucleation mode may cover over 90% of the total particulate number. However, in terms of particle mass, the nucleation mode peak is fairly lower than accumulation mode peak. (Majewski & Khair, 2006, pp. 134-135.) A typical particle size distribution in diesel engine exhaust is presented in Figure 1.

Particle emissions can cause several health effects. Particles with diameter size below 10 µm are inhalable and small enough to penetrate the respiratory system. Effects of exposure to PM emission include respiratory and cardiovascular morbidity but also mortality from cardiovascular and respiratory diseases and from lung cancer. Especially vulnerable groups are elderly people, children and people with pre-existing lung or heart disease. (World Health Organization, 2013, p.6.)

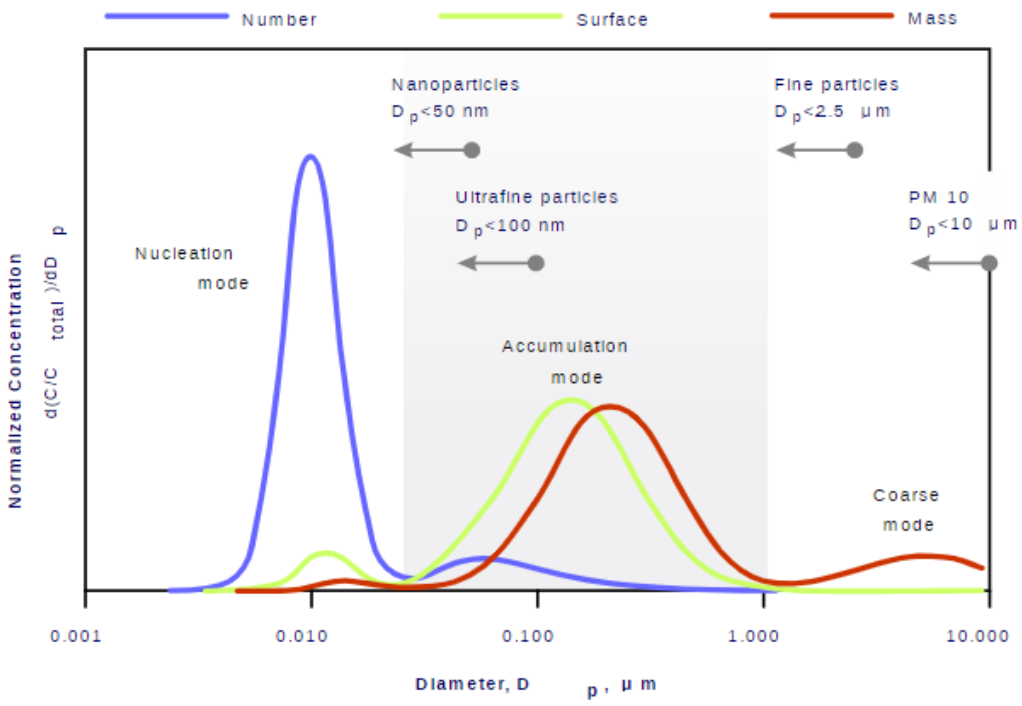


Figure 1. A typical particle size distribution in diesel engine exhaust (DieselNet, 2002).

2.2 EU emission standard and ISO 8178-4 C1 test cycle

In EU, emission standards for non-road engines are named as Stages I-V (DieselNet, 2016). The newest EU Stage V covers wide range of engine sizes and types such as engines for non-road mobile machinery, generating sets, inland water vessels and snowmobiles. (ICCT, 2016, pp. 1, 3-4). Compared to previous EU emission Stages, Stage V set tighter limits for particle mass emissions and also limits PN emissions. Overall, Stage V sets the limits for CO, HC, NO_x, particle mass and PN emissions. Stage V emission standard for non-road engines is presented in Table 1.

ISO 8178-4 standard specifies the test cycles, test procedures and evaluation of gaseous and particulate exhaust emissions from non-road engines coupled with dynamometer. (ISO, 2020; DieselNet, 2001.) Standard includes different steady-state test cycles for different classes of engines and equipment (DieselNet, 2001). Each cycle has modes for different loading points. Each mode has own weighting factor which influence the importance of the emitted gasses at the engine load point. Weighting factors are used

to calculate weighted total emissions over the cycle. (Creten & Van Mullem, 2017, p. 27.) Eight-mode test cycle C1 of ISO 8178 is referred as the NRSC (DieselNet, 2001). Cycle C1 is used for different diesel-powered non-road industrial engines (Winther & Dore, 2019, p.30). ISO 8178-4 C1 is presented in Table 2.

Table 1. EU Stage V emission standards for non-road engines (DieselNet, 2016).

Category	**Ign.**	**Net Power**	**CO**	**HC**	**NO_x**	**PM**	**PN**
		kW	g/kWh				1/kWh
NRE-v/c-1	CI	P < 8	8	7.5[a]		0.40	-
NRE-v/c-2	CI	8 ≤ P < 19	6.6	7.5[a]		0.4	-
NRE-v/c-3	CI	19 ≤ P < 37	5	4.7[a]		0.015	1×10^{12}
NRE-v/c-4	CI	37 ≤ P < 56	5	4.7[a]		0.015	1×10^{12}
NRE-v/c-5	All	56 ≤ P < 130	5	0.19	0.4	0.015	1×10^{12}
NRE-v/c-6	All	130 ≤ P ≤ 560	3.5	0.19	0.4	0.015	1×10^{12}
NRE-v/c-7	All	P > 560	3.5	0.19	3.5	0.045	-

[a] HC+ NO_x

Table 2. ISO 8178 C1 test cycle for non-road engine (DieselNet, 2001).

Mode number	1	2	3	4	5	6	7	8
Torque,%	100	75	50	10	100	75	50	0
Speed	Rated speed				Intermediate speed			Low idle
Weighting factors	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

2.3 Diesel standards

Requirements and test methods for diesel fuel is specified in the EN 590 standard. The standard sets the limit values for several diesel fuel properties such as cetane number, sulphur content and FAME content. (DieselNet, 2015.)

In 2016, the new EN 15940 standard for paraffinic diesel was published. It specifies requirements and test methods for paraffinic diesel fuels such as HVO and FT-products (SFS, 2019a; Neste Corp, 2020, p. 8.) Before the new standard, EN 590 was used to evaluate paraffinic diesel fuel as well. Paraffinic diesel usually meets all limit values of

EN 590 except with density. Due to the low density of paraffinic diesels, the limit for fuel density is lowered by 20 kg/m^3 compared to that of EN590.

Standard EN 14214 specifies requirements and test methods for FAME type diesel fuel either for diesel engines (SFS, 2019b). Specifications of EN 15940, EN 590 and EN14214 standards are presented in Table 3.

Table 3. Paraffinic fuel EN 15940, diesel fuel EN 590 and biodiesel EN 14214 specifications. (DieselNet, 2015; Jääskeläinen, 2009; Neste Corp., 2020, p. 18).

		EN 15940:2016	EN 590:2013	EN 14214:2012
Cetane number		≥ 70	≥ 51	≥ 47
Cetane index		-	≥ 46	-
Density +15 C	kg/m^3	765 - 800	820 - 845	860 - 900
Total aromatics	% (m/m)	≤ 1.1	-	-
Polyaromatics	% (m/m)	-	≤ 8	-
Sulphur	mg/kg	≤ 5	≤ 10	≤ 10
FAME-content	% (V/V)	≤ 7	≤ 7	-
Flash point	°C	≥ 55	≥ 55	≥ 101
Carbon residue on 10% distillation residue	% (m/m)	≤ 0.3	≤ 0.3	-
Ash	% (m/m)	≤ 0.01	≤ 0.01	-
Water	% (m/m)	0.02	≤ 0.02	≤ 0.05
Total contamination	mg/kg	≤ 24	≤ 24	≤ 24
Copper corrosion		Class 1	Class 1	Class 1
Oxidation stability	g/m^3	≤ 25	≤25	-
	h**	≥ 20	≥ 20	≥ 8
Lubricity HFRR at 60 C	µm	≤ 460	≤ 460	≤ 460
Viscosity at 40 C	mm^2/s	2.0 - 4.5	2.0 - 4.5	3.5 - 5.0
Evaporated at 250 C	% (V/V)	≤ 65	≤ 65	-
Evaporated at 350 C	% (V/V)	≥ 85	≥ 85	-
Distillation 95% (V/V)	°C	≤ 360	≤ 360	-
Cloud point	°C	≤ –10*…≤ –34*	≤ –10*…≤ –34*	Location & season dependent
CFPP	°C	≤ +5…≤ –44*	≤ +5…≤ –44*	

*Severe winter and arctic grades

**Additional requirement if contains above 2% (V/V) FAME

3 HVO

HVO is paraffinic liquid fuel which can be produced from different farm-based feedstocks such as rapeseed, sunflower, soybean and palm oil as well as non-food oils like jatropha, algae and tall oil. Animal fats, wastes and residues can be also used as a feedstock. (Aatola et al., 2009, p. 1252.) In the HVO production process hydrogen is used to remove oxygen from vegetable oil creating paraffinic hydrocarbons which typically contain 15 to 18 carbon atoms per molecule. Composition is similar to fossil petroleum diesel which enables using pure or blended HVO without engine modifications. (Douvartzides et al., 2019, pp. 810, 817)

HVO can be used as blending component in fossil diesel fuel or as a neat HVO. As a blending component it increases fuel quality by increasing cetane number, decreasing aromatic content and improving cold start properties. Both ways it has shown to decrease especially HC, CO and smoke emissions in diesel engines. NO_x emission has been either same or lower than with fossil diesel fuel. (Aatola et al., 2008, pp. 1253-1256, 1262.)

Even higher emission reductions can be achieved with engine modifications. According to Bhardwaj et al. (2013, p. 168), the potential of HVO can be improved by optimizing engine hardware and calibrating engine parameters for HVO fuel. For example, reducing compression ratio and optimizing fuel injection position and bowl geometry, may result longer pre-mixed phase and better mixture formation.

Overall, hydrotreatment of vegetable oils results in high-quality renewable diesel which fits existing logistics, engines and exhaust aftertreatment systems without compromising exhaust gas emissions compared to fossil diesel. (Aatola et al., 2008, p. 1251.)

3.1 HVO from CTO

CTO has to be purified from impurities before hydrotreatment can be carried out in hydrogenation reactor (Heuser et al. 2013, p. 819). In hydrotreatment process of CTO hydrogen is used to remove oxygen from the feedstock with suitable catalyst in high pressure and temperature. This process is called hydrodeoxygenation. Double bonds are saturated and O_2 is converted into H_2O. Paraffinic hydrocarbons are created as a final product. (Anthonykutty, 2015, p. 20.) Hydrotreated CTO contains light components and mid-distillate diesel components. These components have to be separated by fractionation. (Heuser et al. 2013, p. 819.) Remaining hydrogen sulphide and incondensable gases are removed and liquid is distilled to separate renewable diesel. (UPM, 2021) Representation of CTO based renewable diesel production is shown in Figure 2.

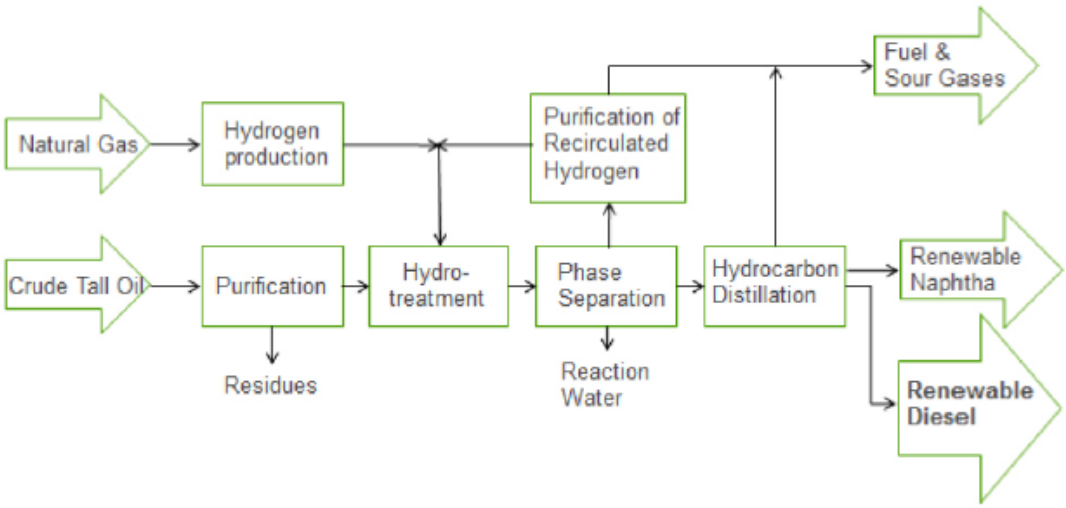


Figure 2. Representation of CTO based renewable diesel production (Heuser et al., 2013, p. 819).

Hydrodeoxygenation is very complex reaction including several deoxygenation steps with cleavage of several chemical bonds before the oxygen is removed. The reaction chemistry is also presumed to be slightly different between tall oil and vegetable oils

because in tall oil fatty acids exist as free acids unlike triglyceride-based vegetable oils. (Anthonykutty, 2015, pp. 20, 43.)

Selecting catalyst is primary criteria to achieve high hydrodeoxygenation conversion. Physical and chemical properties of the feedstock have major influence selecting the right catalyst. Commercial catalysts are mainly based on the elements from group VI and VIII of periodic table. (Anthonykutty, 2015, pp. 20-21.) In addition to hydrodeoxygenation, suitable catalyst can also enable simultaneous hydrodesulphurization, isomerization, hydrogenation and cracking in the reactor. (Heuser et al. 2013, p. 819.)

3.1.1 CTO

CTO is the major by-product from chemical pulping process. In the pulping process acidic components in woodchips are converted into sulphate soaps by cooking with sodium hydroxide and sodium sulphide. Soap layer separates and is skimmed off from the black liquor resulted from the cooking. The sulphite soap is then acidulated into CTO with sulphuric acid. (Anthonykutty, 2015, p. 15; Heuser et al., 2013, p. 818.)

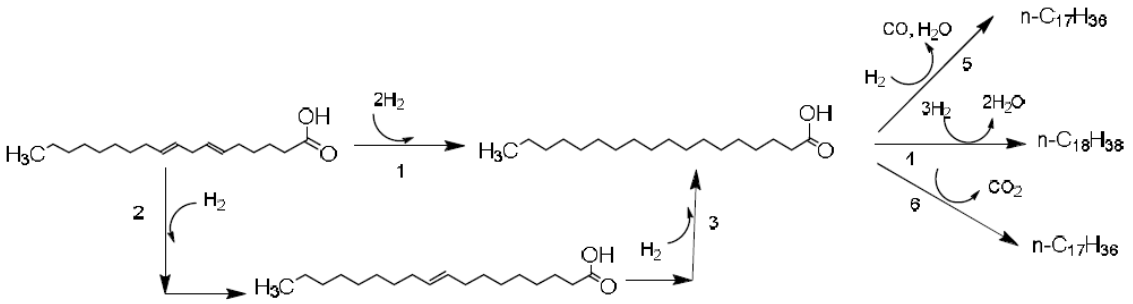
CTO is mainly mixture of fatty acids, resin acids, and neutral substances. CTO´s composition depends on different factors such as species of tree, time of the year, age of the wood and geographical location. The most used wood species is pine which enables the higher fraction of fatty and resin acids in CTO compared to other wood species. (Anthonykutty 2015, p. 16, Heuser et al. 2013, p. 818.) Geographical variation in the composition of CTO is presented in Table 4.

Table 3. Composition of CTO (Anthonykutty, 2015, p. 16).

Composition (wt -%)	South-eastern USA	Northern USA and Canada	Scandinavia
Resin acids	35-45	25-35	20-30
Fatty acids	45-55	50-60	50-60
Neutral components	7-10	12-18	18-24

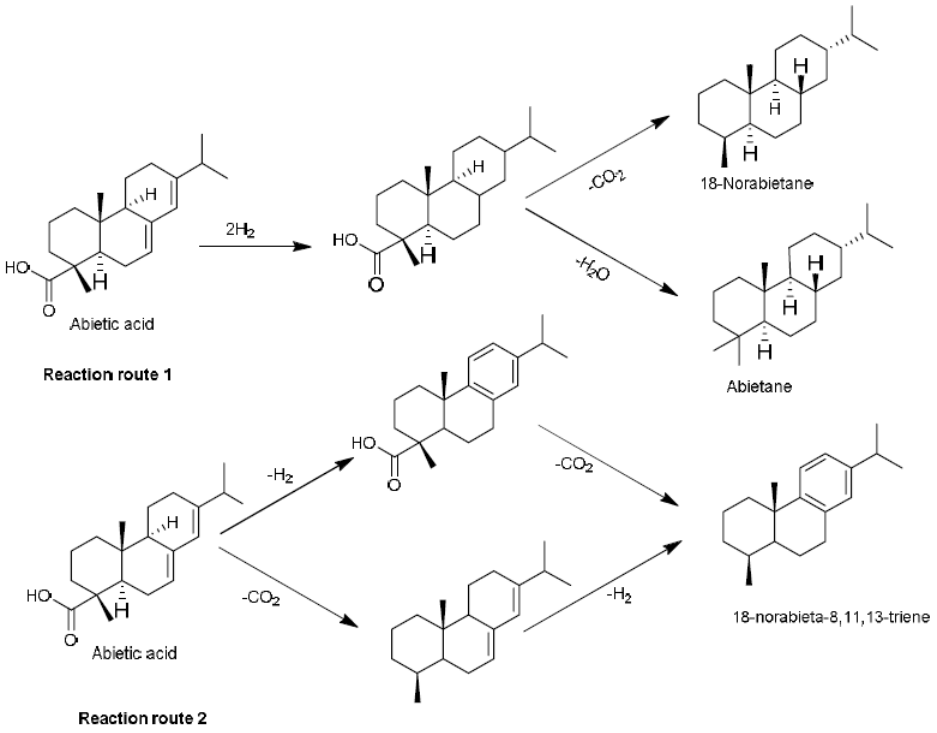
3.1.2 Deoxygenation of fatty and resin acids in CTO

Deoxygenation of fatty acids in tall oil starts with hydrogenation of double bonds in the fatty acid chain which produces intermediate fatty acid (stearic acid). Stearic acid deoxygenates forward in the presence of hydrogen trough three different possible deoxygenation reactions. The reactions are called hydrodeoxygenation, decarboxylation and decarbonylation. These reactions produce paraffinic hydrocarbons as a final product and H_2O, CO and CO_2 are produced as by-products. Hydrodeoxygenation routes of fatty acid are shown in Picture 1. Deoxygenation is usually carried out with hydrotreating catalysts in a fixed bed reactor in temperature of 350-450 °C and pressure from 3 to 10 MPa. (Anthonykutty, 2015, pp. 25, 42-46.)



Picture 1. CTO fatty acids hydrodeoxygenation routes (Anthonykutty, 2015, p. 44).

Deoxygenation of resin acids in CTO differs slightly from deoxygenation of fatty acids. Deoxygenation of resin acids can occur either through two routes which are shown in Picture 2. In the route 1, adiabatic resin acid hydrogenates at first. Created intermediate structure goes then though either decarboxylation or dehydration process. End products are either 18-norabietanes or abietanes. In the route 2, adiabatic resin acid goes through carboxylation and dehydration processes creating norabietatrienes. (Anthonykutty, 2015, pp. 48-48.) Hydrodeoxygenation routes of resin acid are shown in Picture 2. According to the studies by Anthonykutty (2015), it seems that when hydrodeoxygenation is performed under 400 °C the major deoxygenation occurs trough hydrogenation and decarboxylation processes but other deoxygenation processes are also detected.



Picture 2. CTO resin acid hydrodeoxygenation routes (Anthonykutty, 2015, p. 47).

3.2 HVO properties

The hydrocarbon composition of HVO is very similar to the hydrocarbon composition of fossil diesel fuel. This is advantage for the use of HVO when comparing HVO and FAME as a substitute for diesel fuel. (Zeman et al., 2019, p. 346.) Compared to FAME, HVO has lower viscosity, better cold properties and storage stability and produce lower NO_x emissions out of an engine. It does not cause corrosion or swells elastomers in the engine like FAME. (Douvartzides et al., 2019, p. 810.)

HVO has low aromatic, oxygen or sulphur content. It has higher cetane number, higher lower heating value and higher H/C ratio than petroleum diesel. Naturally high cloud point and low lubricity of HVO can be improved by isomerization and with common additives. (Aatola et al., 2009, pp. 1251-1252; Douvartzides et al. 2019, pp. 833, 837.)

Use of HVO leads to significantly lower CO, HC, smoke and particulate emissions compared to use of petroleum diesel and also NO_x emissions reduce. CO_2 emissions are almost same as with petroleum diesel, but biomass-based fuels do not contribute net CO_2 in atmosphere. (Douvartzides et al., 2019, p. 838).

3.2.1 Cetane number

Cetane number defines the ignition quality of diesel fuel. The higher cetane number, the better ignition quality. Ignition quality is linked hydrocarbon composition of the fuel. Paraffins have high ignition quality unlike aromatic compounds which have low ignition quality. (Heywood 2018, p. 571.) High number of paraffinic components and negligible aromatic content in HVO leads to high cetane number (Bhardwaj et al., 2013, p. 158). Paraffins require low activation energy for free radicals' formation to start the combustion process. Branched hydrocarbons and aromatics need higher pressure and temperature to autoignite. (Douvartzides et al., 2019, p. 833)

High cetane number reduces ignition delay which is the time between the start of injection and the start of combustion (Heywood, 1988, p. 505). Shorter ignition delay makes combustion time longer and lowers combustion temperature which result lower NO_x emissions (Aatola et al., 2009, p. 1256). Shorter ignition decreases maximum cylinder pressure and also smoothers increasing of pressure in combustion which lowers noise from the engine (Bhardwaj et al., 2013, pp. 163, 166).

High cetane number usually indicates that engine operate high thermal efficiency and low fuel consumption which enables better fuel economy and lower emissions, since less fuel is burned for same power output (Douvartzides et al., 2019, pp. 833, 836). High cetane number also improves cold start properties and reduces noise from the engine (Bhardwaj et al., 2013, p. 158).

3.2.2 Heating value and density

The heating value is the amount of energy which is released when a unit quantity of fuel is burned. There are two types of heating values, lower and higher heating value. For higher heating value formed water vapour in the exhaust gas is condensed to liquid. For the lower heating value water remains vapour in the exhaust gas. Therefore, higher heating value is higher since condensing water releases energy. Since in the engine exhaust gas water is in gas form, the lower heating value is usually used to describe diesel fuels. (Majewski & Jääskeläinen 2020.)

Heating value can be expressed per unit of mass or volume of fuel. End users buy fuel based on volume hence the volumetric heating value is common in the industry. Heating value per unit volume can be obtained by multiplying the mass-based heating value by the density of the fuel. (Majewski & Jääskeläinen 2020.)

Composition of hydrocarbons determines the density of the fuel. The higher the H/C ratio, the lower the density. (Wang, 2020, p. 88.) HVO has low number of aromatics and unsaturated hydrocarbons which results in a high H/C ratio and low density. Low density means that the volumetric fuel consumption increases. The increase in volumetric fuel consumption is approximately 1.7% when HVO is compared to fossil diesel fuel. (Aatola et al., 2008, p. 1259; Happonen 2012, p. 11.) However, due to the high amount of hydrogen, HVO seems to have higher mass-based heating value, so less fuel in unit mass is needed to get same load and torque than with fossil diesel fuel. This counteract the effect of lower density to some extent. (Douvartzides et al., 2019, p. 833, Zeman et al. 2019, p. 5.)

Lower volumetric heating value makes fuel injection time longer resulting longer combustion time which lowers combustion temperature resulting lower NO_x emissions. (Aatola et al., et al 2009, p. 342.)

3.2.3 Distillation

Distillation properties show how the fuel evaporates when it is injected into the combustion chamber of the diesel engine. Fractions with low boiling point are important for engine's start-up. High boiling, heavier fractions can cause incomplete combustion of the fuel and increase harmful emission in the exhaust gas. HVO contains low amount of high boiling fractions. (Zeman et al. 2019, pp. 342-343.)

Bhardwaj et al., (2013, p. 161) studied boiling behaviour of fossil diesel fuel, rapeseed methyl ester (RME) and HVO. Diesel fuels have a wide distillation range (200-300 °C) mainly due to mixture of 200 different types of hydrocarbons. RMEs distillation range is very narrow (350-360 °C) and boiling temperature is high. This indicates poorer evaporation. HVOs have a lower distillation range than diesel fuels within approximately 250-290 °C. Better evaporation behaviour of HVO enables improved mixture formation in the combustion chamber and it reduces engine emissions.

3.2.4 Viscosity

Viscosity indicates fuels resistance to flow. The higher viscosity, the higher the resistance to flow. Viscosity correlates strongly with temperature. This is why viscosities that are shown in fuel specifications are measured at standard temperature. For diesel viscosity is commonly measured at 40 °C. (Majewski & Jääskeläinen, 2020.) Low number of aromatics in HVO results in low viscosity (Jeihouni, 2011, p. 7).

Low temperature problems such as restricted fuel flow, damages to pump and injector or high frictional forces can occur if viscosity is too high. On the other hand, if viscosity is too low, problems such as increased leakages and poor lubrication of fuel can occur. Leakages in pumping elements can lower injection pressure resulting hot start and engine acceleration difficulties. (Majewski & Jääskeläinen, 2020.)

Viscosity affects fuel spray atomization and fuel system lubrication (Jehouni et al., 2011, p. 7). It is possible that lower viscosity of HVO can allow a better mixing of the fuel droplets with air which reduces ignition delay (Douvartzides et al., 2019, p. 836).

3.2.5 Cold properties

Cloud point signifies the highest temperature below where solid wax crystals start to form in the fuel. These crystals can collect in filters which can lead to blockage of the fuel system. (Jääskeläinen 2017.) High cloud point makes the fuel impractical for use as an engine fuel (Douvartzides et al., 2019, p. 833).

Due to the high content of n-paraffins, raw HVO has high cloud point. However, lower cloud point can be achieved via isomerization which converts n-paraffins in the HVO to iso-paraffins. Higher amount of iso-paraffins in the fuel improves cold properties. (Smagala et al., 2013, p. 243.) Isomerization does not change the density of the fuel but lowers the cetane number (Douvartzides et al., 2019, p. 833). Smagala et al. (2013, pp. 242,246) studied effect of isomerization on the cetane number and the cloud point of HVO. Study showed that HVO, which has a cetane number of 118 and cloud point of 20 °C, can be converted to HVO, the cloud point of which is -20 °C and cetane number still above 70. This enables the use of HVO in the colder environments as well.

3.2.6 Lubricity

Lubricity is important in diesel engine since the fuel pumps and the fuel injectors are high precision equipment which are manufactured with highest possible geometrical accuracy and operating with highly loaded contacts. (Douvartzides et al., 2019, p. 833.)

Due to the low amount of sulphur, oxygen and aromatic compounds, HVO has low lubricity (Lapuerta et al. 2011, p. 2406; Zeman et al. 2019, p. 342.), approximately 700 µm (Douvartzides et al., 2019, p. 834). Lubricity enhancers has to be added to the fuel

so it meets the lubricity requirements of EN 590 standard. Same commonly used lubricants for diesel can be used with a similar dosage. (Zeman et al. 2019, p. 342.)

3.2.7 Storage properties

HVO has good oxidation and thermal stability due to the lack of unsaturated hydrocarbons (Smagala et al., 2013, p. 240).

HVO can be handled in a similar way as a fossil diesel fuel. Storage stability and water solubility of HVO are very similar to fossil diesel fuels. Due to the similarities with fossil diesel, no modifications are needed in pipelines, storage tanks or service stations. (Nylund et al., 2011, p. 32.)

3.2.8 Sulphur

HVO contains a low amount of sulphur (Aatola et al., 2009, p. 1251). Sulphur in diesel fuel has negative impact on the emissions and emission control catalyst. Most of the sulphur in the fuel converts into sulphur dioxide which has negative impact on the environment. Part of the sulphur oxidises to sulphur trioxide which converts to sulphur acids resulting higher PM emissions. Sulphur also causes corrosion in the engine and increase wear of the engine parts. (Majewski & Jääskeläinen, 2020)

3.3 Previous studies

Niemi et al. (2016) studied how different blends of CTO based renewable diesel and neat CTO affect to exhaust emissions in non-road diesel engine. In the study the test engine had tuned to high NO_x and no exhaust gas after-treatment system. The study was conducted according NRSC while the engine's rated speed was 2200 rpm and intermediate speed was chosen to be 1500 rpm. The study showed that CO and HC emissions decreased with increasing share of CTO based renewable diesel in blend. With 100% renewable diesel approximately 15% reductions were achieved in CO emission. HC emissions reduced by 21%. NO_x emissions, however, were almost constant and

significant reductions were not detected. In terms of PN, the total PN over the NRSC cycle decreased with increasing share of renewable diesel in the blend.

Aatola et al., (2009) studied how the use of HVO affects emissions in heavy duty diesel engine at the speed of 2200 rpm, 1500 rpm and 1000 rpm. Neat renewable diesel and also blend, consisting of 30% HVO and 70% fossil diesel fuel, were studied. Reductions were detected in HC, CO and NO_x emissions when HVO or HVO blend was used. In HC and CO emissions, reductions were approximately 30% with 100% HVO and approximately 14% with the blend. NO_x emissions reduced 5% with HVO but increased very slightly with the blend.

Heikkilä et al. (2012) studied how Miller timing and start of injection affects NO_x, PN and particle mass emissions of HVO fuelled non-road diesel engine. Studied fuels were 100% HVO diesel and EN590 diesel fuel. On standard engine settings NO_x, PN and particle mass were lower with HVO than with EN590 diesel fuel. The study showed that with adjusting engine settings even more reduction can be made. Effects of advanced intake valve closing (IVC) and start of injection (SOI) timing studies were conducted at 100% load. When IVC were advanced, NO_x emission decreased, but PN and particle mass increased. On the contrary advancing start of ignition PN and particle mass decreased and NO_x were slightly higher. Best results were achieved with advanced IVC (-50 and -70 °CA) combined with advanced SOI. Then both, PM and NO_x, were reduced. However, optimum combination depends on the required emission level and used after-treatment system.

Compared to Heikkilä et al. (2012), Lehto et al. (2012) received similar results in NO_x and PM emissions with Miller timing and advanced SOI. Without any changes in engine parameters reduction in NO_x emissions were 2-5% and in PM 40%. With advanced SOI and sufficient Miller timing more reduction in NO_x and PM were achieved.

Hajbabaei et al. (2012) studied NO_x emissions from animal-based and soy-based FAMEs and renewable and gas-to-liquid diesels in heavy-duty engine. Fuels were tested neat and as blended to baseline diesel. California Air Resources Board (CARB)-certified diesel

was used as a baseline fuel. Study showed that NO_x increased when biodiesel share increased in the blend. With renewable diesel and gas-to-liquid diesel NO_x emissions decreased with increasing blend level.

4 Experimental setup

In this chapter test engine, analysers, fuels and experimental matrix are presented. The study was performed by the University of Vaasa at the engine laboratory of the Technobothnia laboratory unit in November 2020.

4.1 Test engine

The engine used in this study was AGCO POWER 44 AWI. It was a turbocharged, intercooled (air-to-water) non-road diesel engine which had a common rail fuel injection system. The engine had no exhaust aftertreatment system. The specifications of the test engine are given in Table 5.

Table 4. Test engine specifications

Engine	AGCO POWER 44 AWI
Cylinder number	4
Bore (mm)	108
Stroke (mm)	120
Swept volume (dm^3)	4.4
Rated speed (rpm)	2200
Rated power (kW)	101
Rated maximum torque at rated speed (Nm)	446
Maximum torque at 1500 rpm (Nm)	560

4.2 Analysers

A Horiba SPARC controller platform was used to control engine speed, torque and throttle during the study. The engine control parameters were followed by using AGCO SISU Power WinEEM4 service tool, while the LabVIEW system-design software was used to monitor and record engine temperatures and pressures. Table 6 lists the measurement instruments that were used to determine the mass flows of intake air and fuel plus the cylinder pressure and various exhaust emissions.

Table 5. Measurement instruments

Measuring device	Measured variable
Eco Physics CLD 822 M hr	NO_x
J.U.M engineering THC analyser VE7	HC
Siemens Ultramat 6	CO
AVL Smoke Meter	Smoke
TSI EEPS 3090	Particle size distribution and PN
Gasmet FT-IR gas analyser DX4000	CO_2
Kern	Fuel mass flow

In order to determine the exhaust PN, the sampled raw exhaust was first diluted with a rotating disc diluter (model MD19-E3, Matter Engineering AG). The dilution ratio was constant 60:1. For the EEPS, the diluted sample was further diluted by purified air with a dilution ratio of 2:1, giving the overall dilution ratio of 120:1.

4.2.1 NO_x

NO_x concentration in the exhaust gas were measured with Eco Physics CLD 822 Mhr modular gas analyser from dry exhaust gas. Analyser's working principle is based on chemiluminescence reaction. NO in the exhaust gas sample reacts with ozone in the measurement chamber resulting NO_2 molecules. Reaction releases chemiluminescence radiation which is used to determine NO_x in the exhaust gas sample. (Ecotech, 2010.)

4.2.2 CO

CO concentration in exhaust gas were measured with Siemens Ultramat 6 gas analyser from dry exhaust gas. Analyser's operation is based on the infrared absorption by the sample gas components. Nitrogen is used as reference gas since it is non-infrared active gas. Heated infrared source is divided into sample and reference beams. Reference beam passes through the reference gas unattenuated and sample beam passes through the sample gas attenuated. (Siemens AG, 2018.) Infrared absorbed by the sample gas at the appropriate frequency is measured and the CO concentration can be determined (Lee & Kester, 2016, p. 1.).

4.2.3 HC

HC concentration in exhaust gas were measured with J.U.M engineering THC analyser. It uses the heated flame ionization method to determine total hydrocarbon concentration in exhaust sample. At first hydrogen is burned in hydrocarbon-free air. When exhaust gas sample containing organic carbon is introduced with burning hydrogen, complex ionization process will start. Ions from the process are then exposed to high polarizing voltage creating electrostatic field. Negative carbon atoms migrate to the collector electrode and positive hydrogen ions migrate to the high voltage electrode. The generated ionization current between the electrodes is directly proportional to the HC concentration. (J.U.M engineering, 2020.)

4.2.4 CO_2

CO_2 emission were measured with Gasmet FT-IR gas analyser from wet exhaust gas. Analyser uses Fourier Transform Infrared (FTIR) spectroscopy technology to measure contents in the exhaust gas. Operation is based on the infrared absorption by the sample gas components. Spectrometer scans and analyses the entire infrared spectrum from which molecule contents in the exhaust gas sample can be determined. (Gasmet, 2020; Lee & Kester, 2016, p. 1.)

4.2.5 Particle size and PN

TSI EEPS 3090 particle sizer spectrometer was used to measure particle size distribution and PN in the exhaust gas. Spectrometer measures size distribution and number concentration in diluted exhaust gas. Measurement range for particle size is from 5.6 to 560 nm and concentration can be measured as low as 200 particles/cm^3. In the measurement process, 10 dm^3/min diluted exhaust gas is drawn into the inlet continuously. Particles are positively charged predictable level using corona charger. Charged particles are then moved to measurement region near the centre of a high-voltage electrode column. Electric field is created by applying a positive voltage to the electrode. According to the particles electrical mobility electric field repels the positively

charged particles outward to the respective electrometers where particle transfer their charge from which the concentration can be determined. (TSI, 2016.)

In this study exhaust gas sampling rate of EEPS was adjusted at 5.0 dm^3/min before the measurement. The recorded smoke value was written down as the average of three consecutively measured smoke numbers.

Based on the concentrations of gaseous emissions, specific values of gaseous emissions were calculated according to the ISO 8178 standard. For the results of the PN and size distributions, three-minute time intervals were chosen during which the total particle concentration was as stable as possible. The average values with the standard deviation were calculated from the measured particle numbers during these three-minute time intervals. They were multiplied by the dilution ratio of the exhaust gas sample.

4.3 Fuels

Two renewable diesel fuels and one renewable diesel fuel blend were studied in the test engine. BVN, BVO were both Finnish renewable diesels which were derived from crude-tall oil by hydrotreating. DFO, fossil diesel fuel oil, was used as a reference fuel. Fuel blend consisted of 50 vol.-% BVN and 50 vol.-% DFO. Fuel specifications are given in Table 7.

Each fuel was studied separately on a different day.

Table 6. Fuel specifications

Parameter	Unit	DFO	BVN-DFO	BVN	BVO
Fuel share	vol.-%	100	50:50	100	100
Cetane Number	-	57.5	61.5	65.2	61.6
Cetane Index	-	57	63.4	71.2	66.1
Density (15C)	kg/m^3	836	826	815	813
PAH content	% (m/m)	2.7	1.4	0.1	0.1
Sulphur content	mg/kg	7.9	<5	<5	<5
Flash Point	°C	67.5	73	77	73
Carbon residue (10% Dist.)	% (m/m)	<0.10	<0.01	<0.10	<0.10
Ash Content (775 °C)	% (m/m)	<0.001	<0.001	<0.001	<0.001
Water content	mg/kg	32	19	21	22
Total contamination	mg/kg	<12	<12	<12	<12
Copper strip corrosion	Korr.Grad	1	1	1	1
Fatty acid methylester content	% (V/V)	<0.1	<0.1	<0.01	<0.01
Oxidation stability	g/m^3	<1	<1	<1	<1
Oxidation stability	h	>48	>48	43.6	42.1
HFRR	µm	380	430	560	380
Kin. Viscosity	mm^2/s	3.33	3.43	3.55	2.81
%(V/V) recovery at 250 °C	% (V/V)	23	20	16	33
%(V/V) recovery at 350 °C	% (V/V)	93	93	92	93
95% (V/V) recovery	°C	354	358	372	367
CFPP	°C	-12	-14	-14	-8
Manganese (Mn)	mg/l	<0.5	<0.5	<0.5	<0.5
Caloric value, upper	MJ/kg	45.6	46.0	46.5	46.6
Caloric value, lower	MJ/kg	42.8	43.2	43.4	43.6

4.4 Experimental matrix

The measurements were conducted at eight load points (modes 1-8). The load points were selected according to the C1 driving cycle of ISO 8178. The rated speed of the test engine was 2200 rpm and the idle speed 860 rpm. The intermediate speed was 1500 rpm. Table 4 presents speeds, loads, torques and the NRSC weighting factors for the different modes.

Table 7. Experimental matrix

Mode	1	2	3	4	5	6	7	8
Speed (rpm)	2200	2200	2200	2200	1500	1500	1500	860
Load (%)	100	75	50	10	100	75	50	0
Torque (Nm)	446	334	223	45	560	420	280	1
Weighting factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

Before the measurements, it was waited that the engine run had been stabilized. The main criteria were that the temperatures of intake air in the manifold and exhaust upstream of the turbine were stable. At Mode 1, the intake air temperature was set at 50 °C. At modes 2-7, the temperatures decreased with engine load varying between 30 °C and 50 °C. At idle the intake air temperature was approximately 12 °C with all fuels.

5 Results

In this chapter the main results of this study are presented.

5.1 Test conditions

Figure 3 shows the ambient air temperature and Figure 4 the relative humidity during the test cycles. Air temperature varied between 32 °C and 42 °C. The relative humidity was between 11% and 21% during the measurement days. Since the temperature and humidity were fairly similar during each measurement day, the ambient conditions should not affect the results significantly.

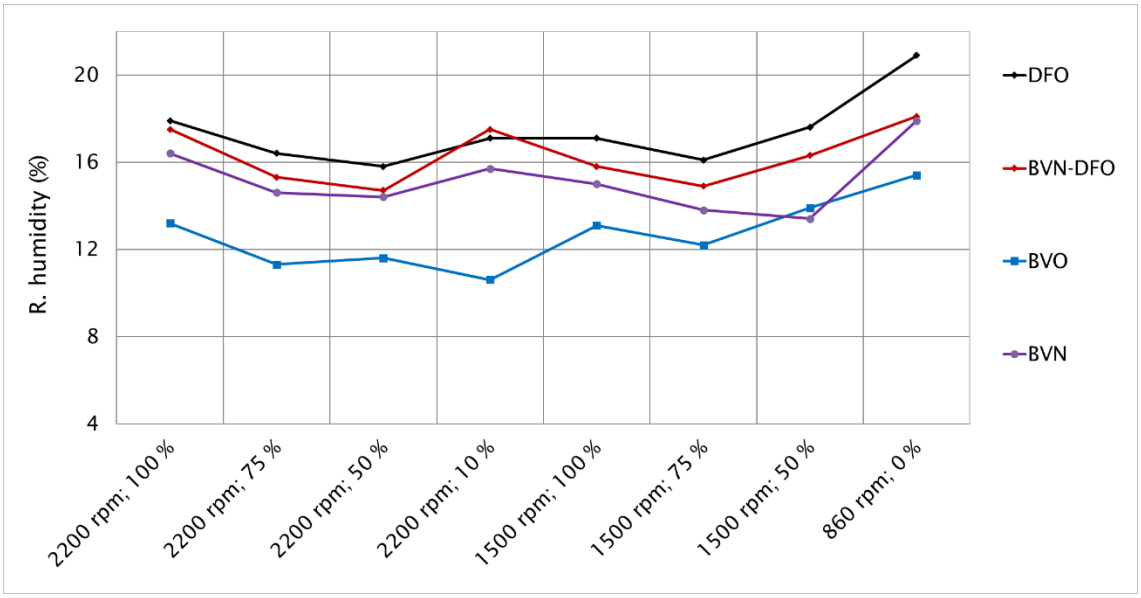


Figure 3. Ambient air temperature during the test cycles.

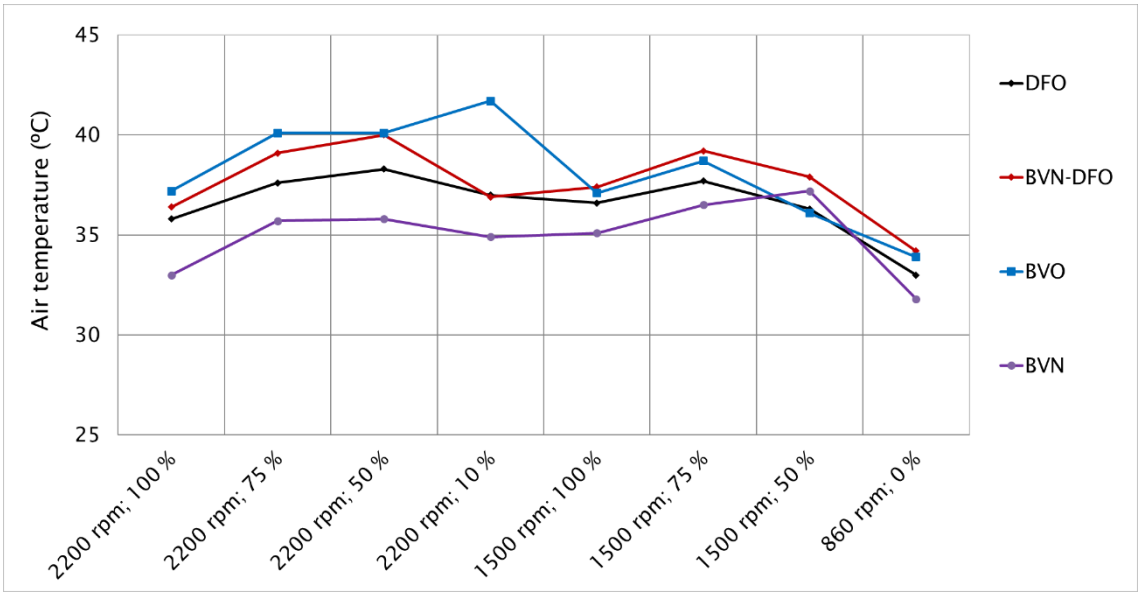


Figure 4. Relative humidity during the test cycles.

5.2 Efficiency

Figure 5 shows the engine efficiencies for different fuels at rated speed and Figure 6 at intermediate speed. At both speeds, efficiency increased with increasing load with all fuels, as usual. At the rated speed at full load efficiency was the highest with DFO (39%) and the lowest with BVO (38%). At 10% load efficiency stayed between 15-16% with all fuels. At intermediate speed, the highest efficiency was at full load with DFO (41%). At both speeds, the differences between the fuels were minor, at their highest approximately 1 percentage point at every load.

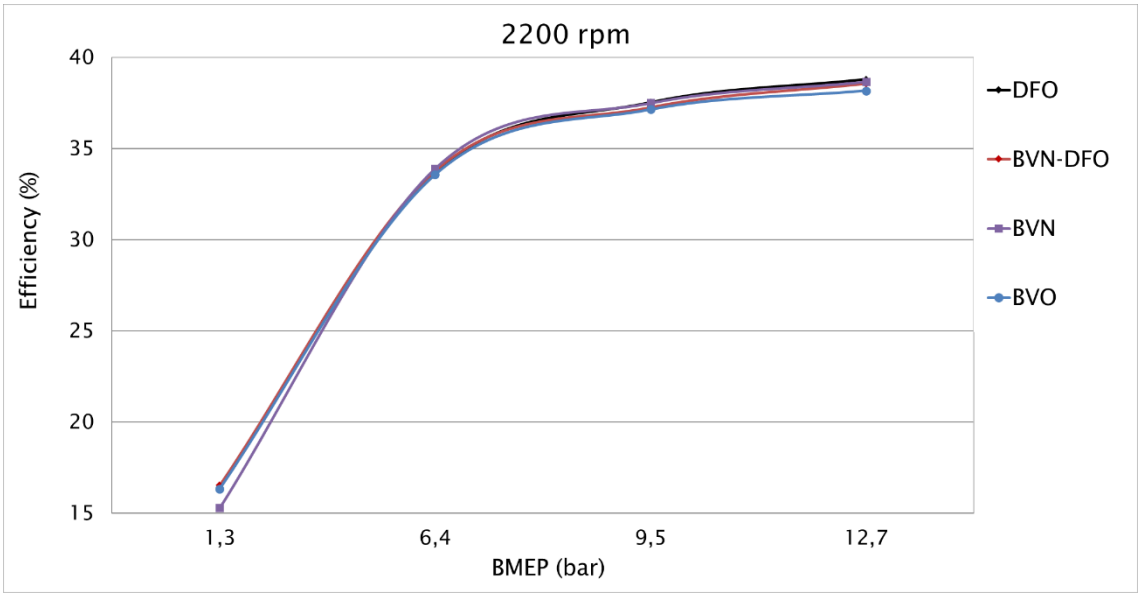


Figure 5. Engine efficiency at 2200 rpm

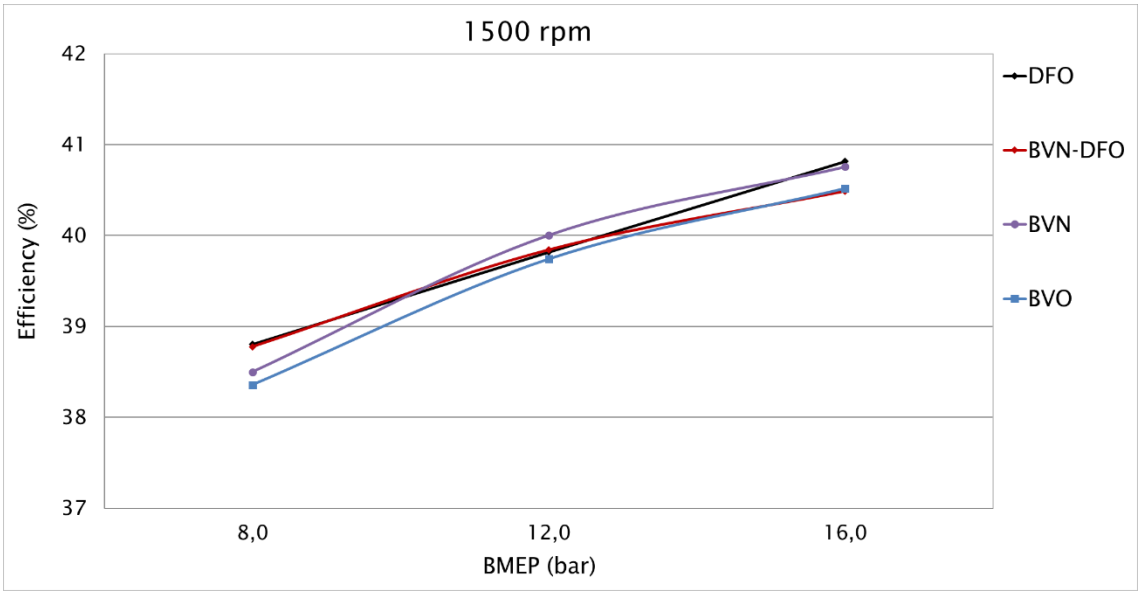


Figure 6. Engine efficiency at 1500 rpm

5.3 Gaseous and PN emissions

NO_x, CO and HC emissions have been presented as brake specific emissions at different loads and also as weighted brake specific emissions over the cycle. CO_2 has been given as a wet exhaust content (in %). PN emissions have been presented as particle size distributions at different load points, as brake specific PN at different loads and also as a weighted PN over the cycle.

5.3.1 NO_x

Figure 7 shows the brake specific NO_x emissions versus engine load at rated speed and Figure 8 for intermediate speed. At rated speed, emissions were the highest at 10% load where NO_x emissions varied from 12.1 g/kWh to 13.4 g/kWh. At half load emissions reduced by half and stayed the same level at 75% and full load, varying between 6.2 g/kWh and 7.2 g/kWh. At intermediate speed, NO_x emissions were between 7.5 and 9.1 g/kWh at all loads.

BVO seemed to be the most favourable at both speeds. BVN and BVN-DFO emitted almost same NO_x at same loads except that at full load at intermediate speed BVN-DFO came out slightly more beneficial. The NO_x emissions were highest when DFO was used.

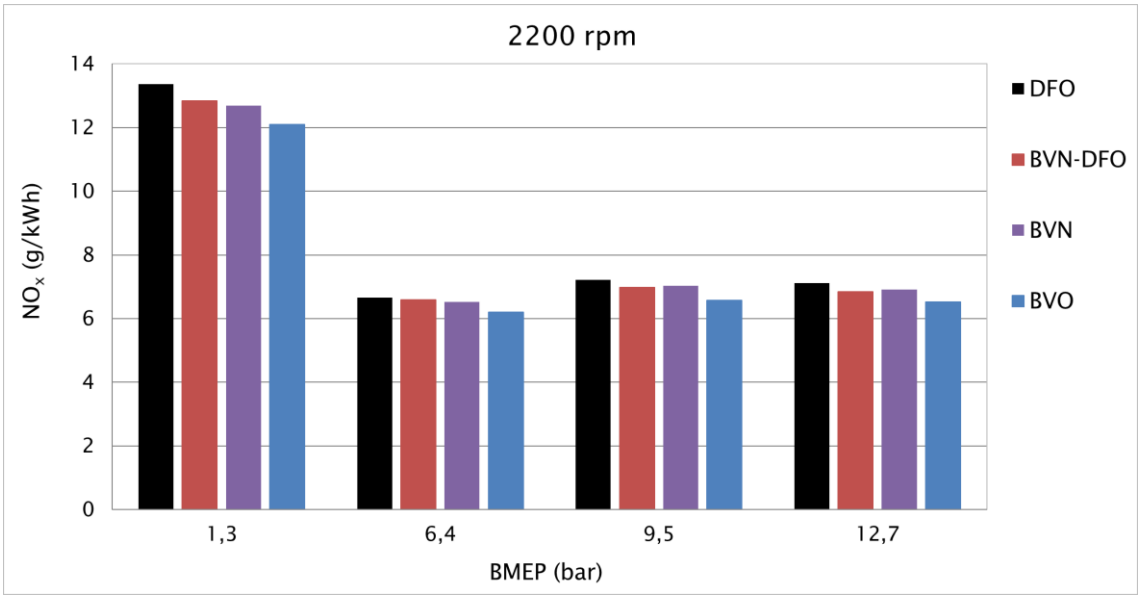


Figure 7. Brake specific NO_x emissions versus engine load at 2200 rpm.

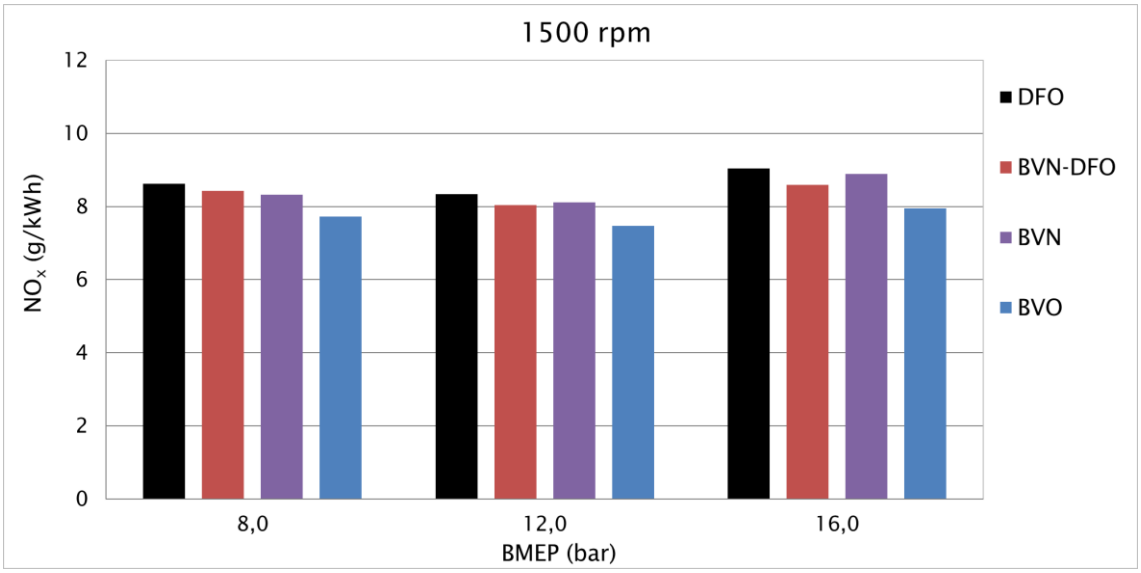


Figure 8. Brake specific NO_x emissions at load points at 1500 rpm.

Figure 9 shows the brake specific NO_x emissions over the cycle. Figure 10 shows the relative changes in the cycle-weighed NO_x emissions for different fuels. NO_x emissions varied between 7.1 and 7.9 g/kWh over the cycle. Overall, throughout the cycle, renewable diesels and diesel blends emitted less NO_x than DFO. NO_x emissions were the lowest with BVO, approximately 9% below the baseline DFO. Between BVN and BVN-DFO there were basically no difference in NO_x emissions and 3% reduction were achieved with these fuels.

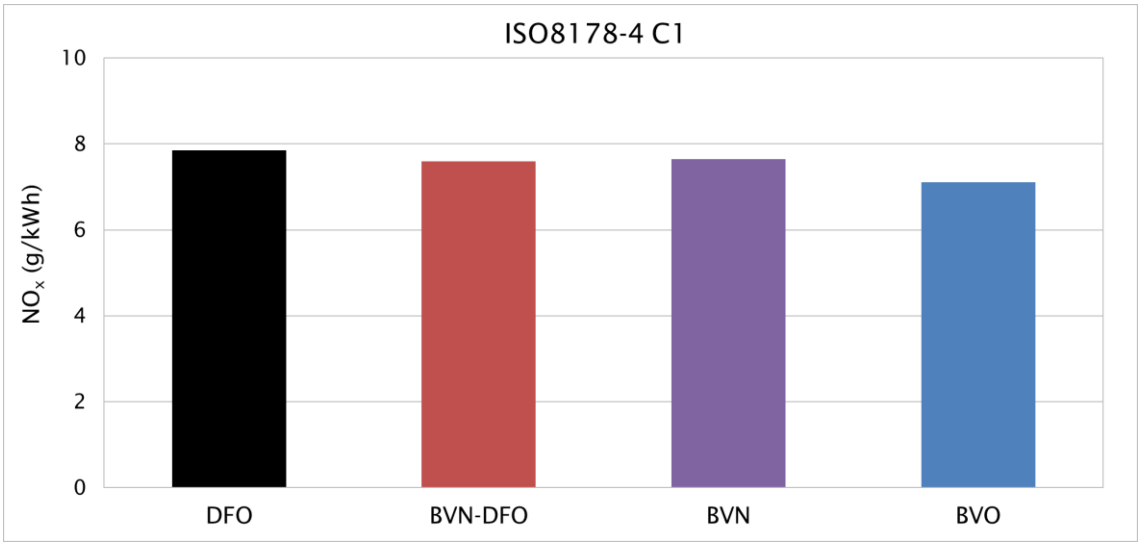


Figure 9. Brake specific NO_x emissions over the cycle.

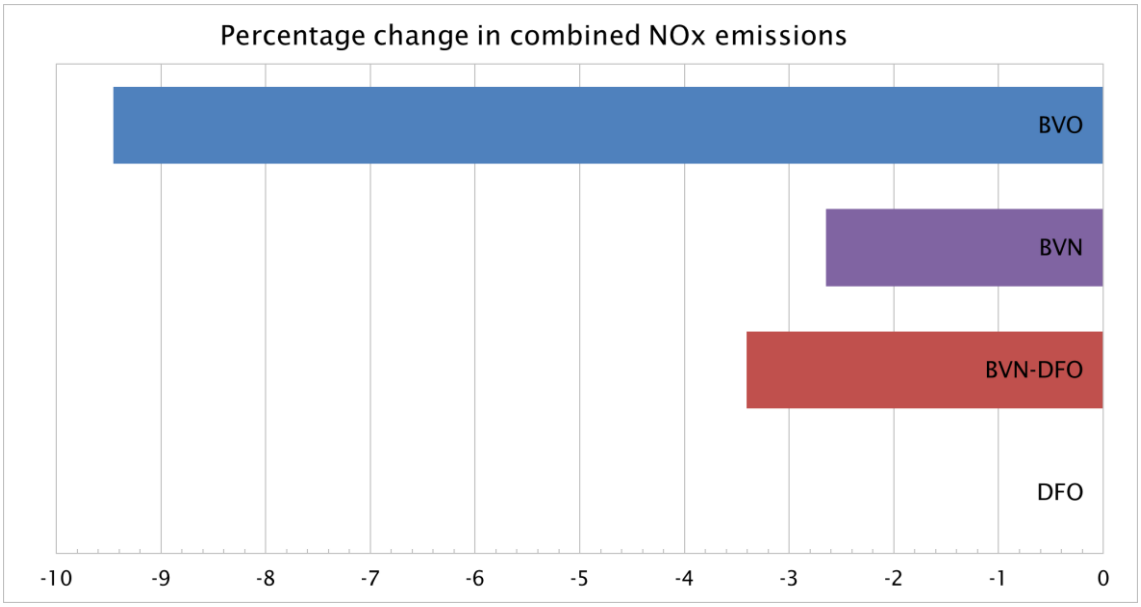


Figure 10. Relative changes in the cycle-weighted brake specific NOx emissions for different fuels and fuel blends. DFO forms the baseline.

5.3.2 CO

Figure 11 shows the brake specific CO emissions versus engine load at rated speed. CO emissions were the highest at 10% load and decreased to half at half load. At 10% load CO emissions were between 1.3 and 1.5 g/kWh and at half load between 0.6 and 0.7 g/kWh. At 75% and full load CO results were quite even varying between 0.15 g/kWh and 0.19 g/kWh.

Figure 12 shows the brake specific emissions versus engine load at intermediate speed. The CO emissions were highest at half load where CO emissions were between 0.16 g/kWh and 0.18 g/kWh. At 75% load CO decreased and varied from 0.09 g/kWh to 0.11 g/kWh. At full load CO levels increased again slightly and were between 0.11 g/kWh and 0.13 g/kWh.

At 10% and half loads, at rated speed, a beneficial trend can be detected with renewable fuels and with blend. BVO and BVN seemed to be slightly more beneficial than BVN-DFO. At higher loads, as well as all loads at intermediate speed, BVO, BVN or BVN-DFO seem

not have any clear advantages over DFO and the differences between the fuels were minor.

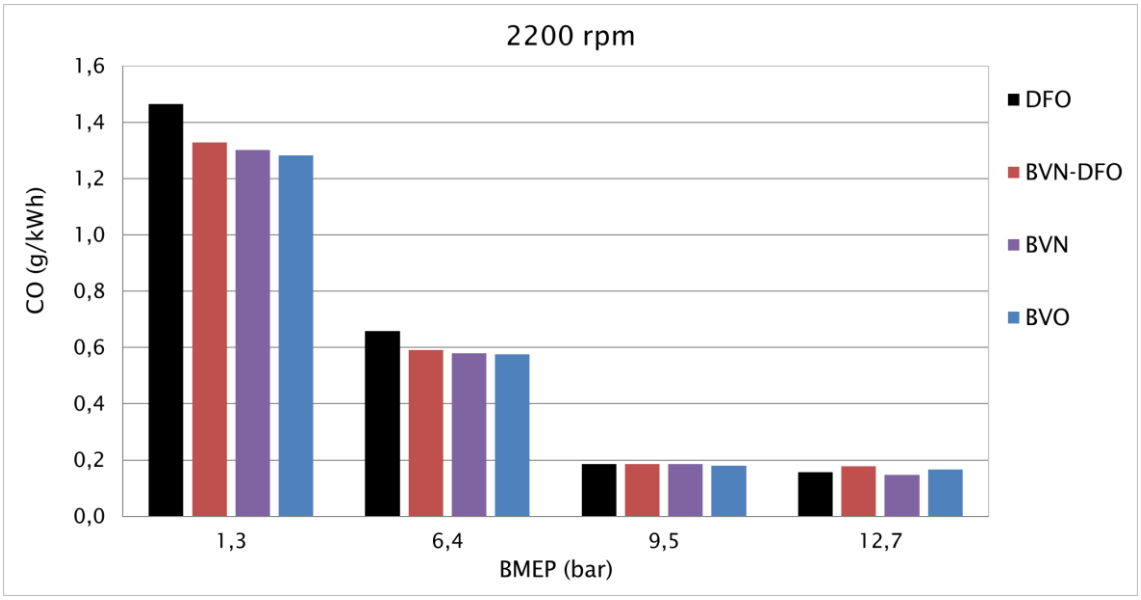


Figure 11. Brake specific CO emissions versus engine load at 2200 rpm.

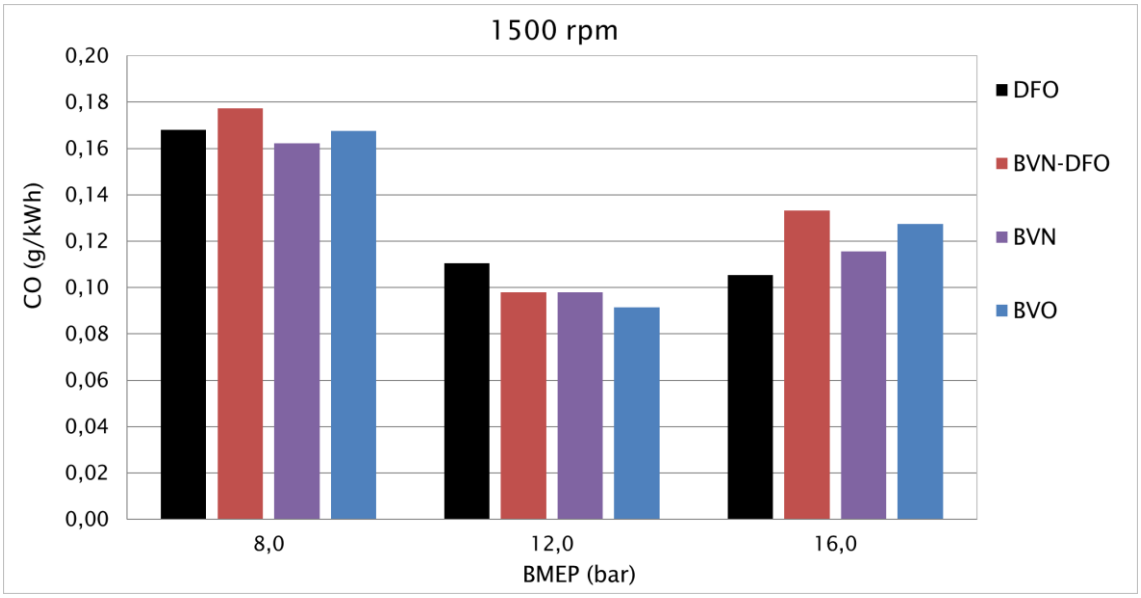


Figure 12. Brake specific CO emissions versus engine load at 1500 rpm.

Figure 13 shows the brake specific CO emissions over the cycle. CO emissions were the lowest when BVN was used (0.24 g/kWh) and CO emissions were the highest with DFO (0.27 g/kWh). Over the cycle, all renewable diesels and diesel blend managed better

than DFO. However, in terms of individual loads, at full load at both speeds, renewable diesels and blend did not seem to be as favourable as DFO.

Figure 14 shows the percentage changes in the cycle-weighed CO emissions for studied fuels relative to DFO. BVN was the most beneficial achieving a 9% CO reduction. With BVO emissions reduced by 6% and with BVN-DFO by 2%.

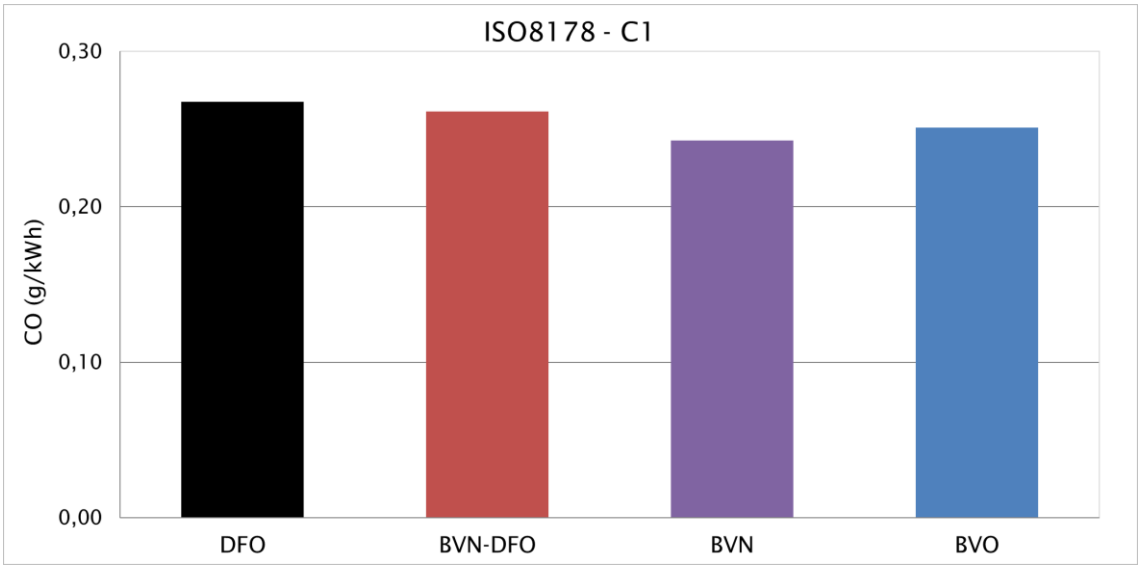


Figure 13. Brake specific CO emissions over the cycle.

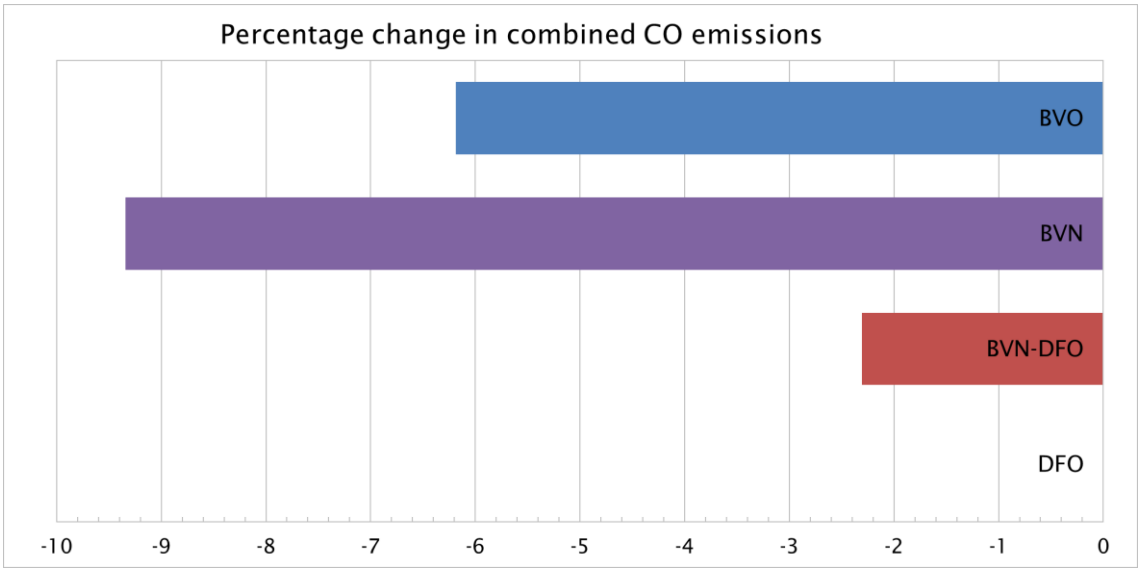


Figure 14. Percentage changes in the cycle-weighted brake specific CO emission for studied fuel options.

5.3.3 HC

Figure 15 shows the brake specific HC emissions versus engine load at rated speed. Figure 16 shows the brake specific HC emissions at intermediate speed. At both speeds, HC emission decreased with increasing engine load. At 10% load at rated speed, where HC emissions were the highest, results varied between 0.8-0.9 g/kWh. At half load emissions decreased to 0.21-0.25 g/kWh. At 75% and at full load differences in HC emissions were minor varying between 0.07 g/kWh and 0.1 g/kWh. At half load at intermediate speed, result varied between 0.12 g/kWh and 0.15 g/kWh and at 75% and at full load the results were between 0.06 g/kWh and 0.08 g/kWh.

The HC emissions were highest with DFO at most load points at both speeds except at full load at rated speed BVO emitted slightly more HC. However, at rated speed, while the load increased the differences between the fuels became more even and at 75% and at full load there is hard to make any significant conclusions based on the results.

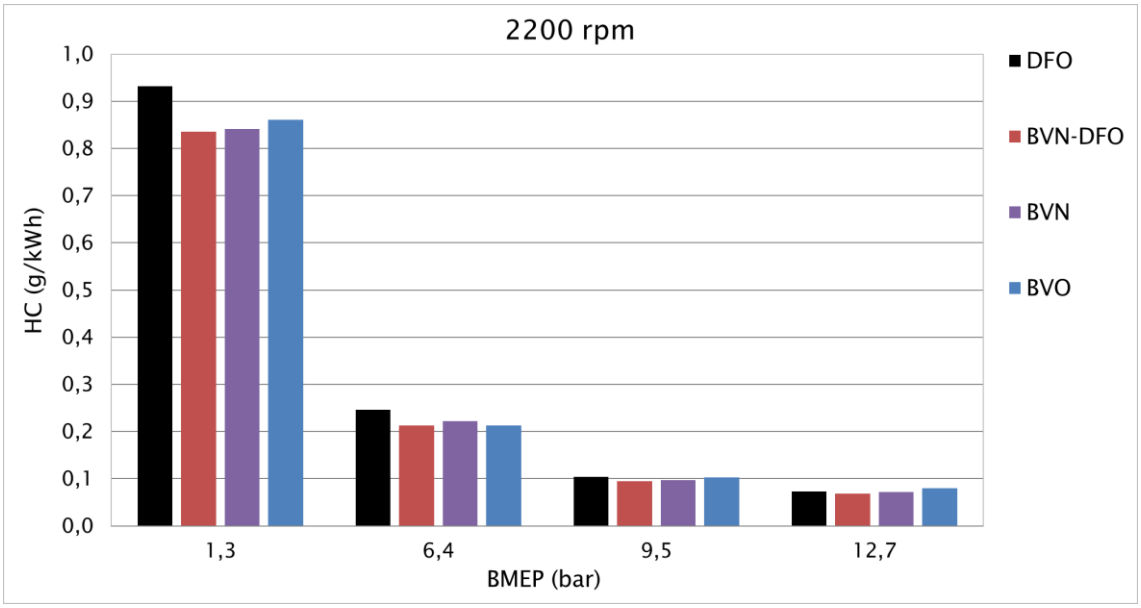


Figure 15. Brake specific HC emissions at load points at 2200 rpm.

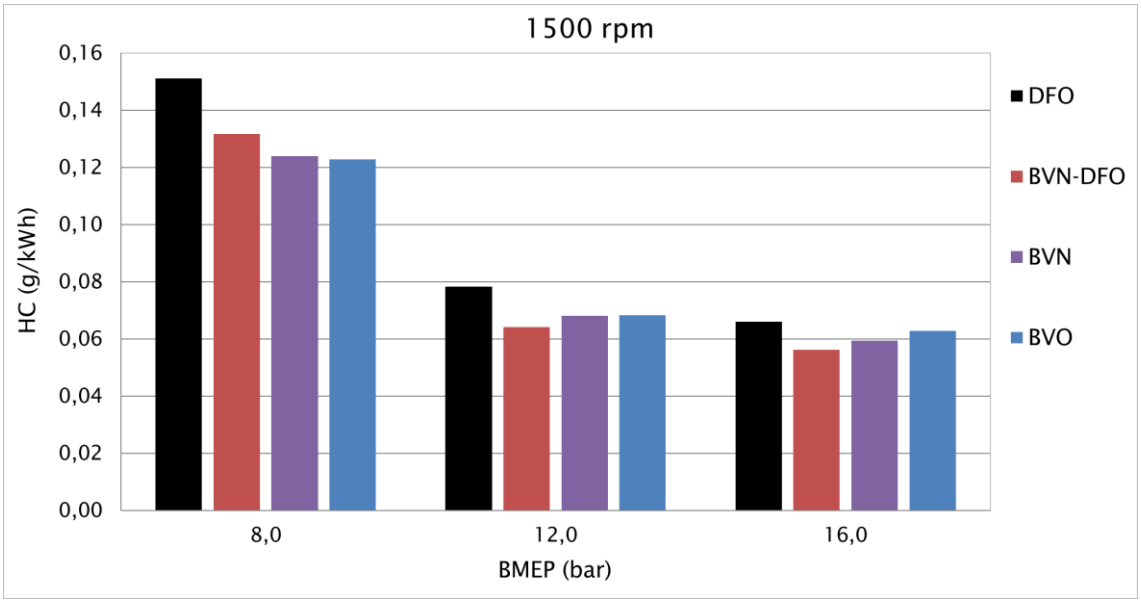


Figure 16. Brake specific HC emissions at load points at 1500 rpm.

Figure 17 shows the brake specific HC emissions over the cycle. The HC emissions were lowest with BVN-DFO (0.12 g/kWh) but BVN seemed almost as favourable as well. HC were highest with DFO (1.4 g/kWh). All studied fuels emitted less HC than DFO. The percentage reductions of the HC emissions for the studied fuels are shown in Figure 18. BVN-DFO and BVN seemed to be most favourable with 10-12% reductions in HC emissions compared with DFO. With BVO reduction was 6%.

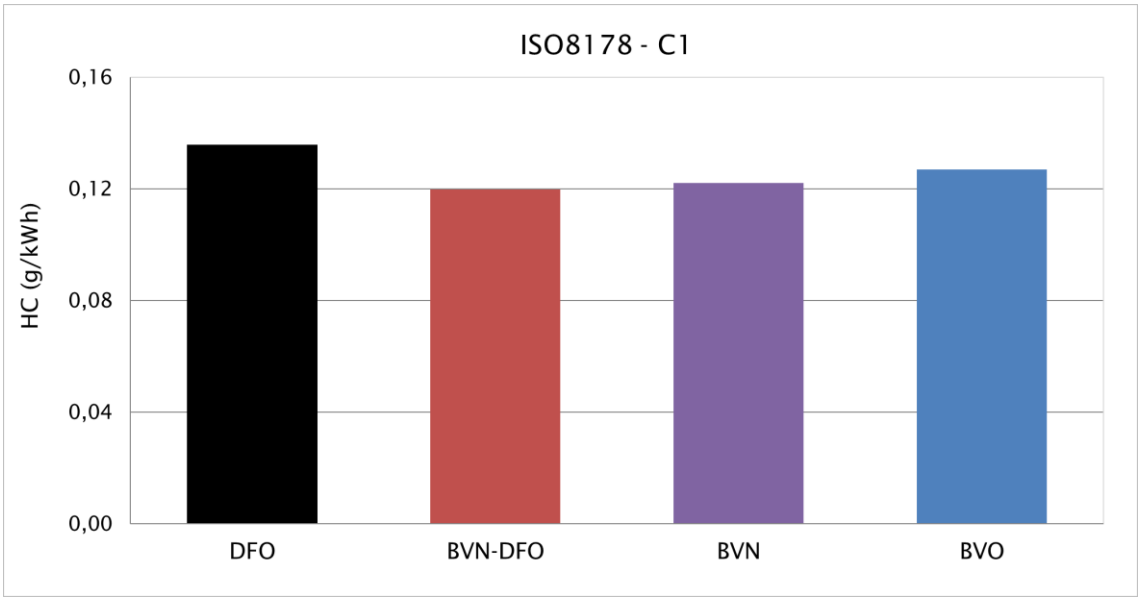


Figure 17. Brake specific HC emissions over the NRSC.

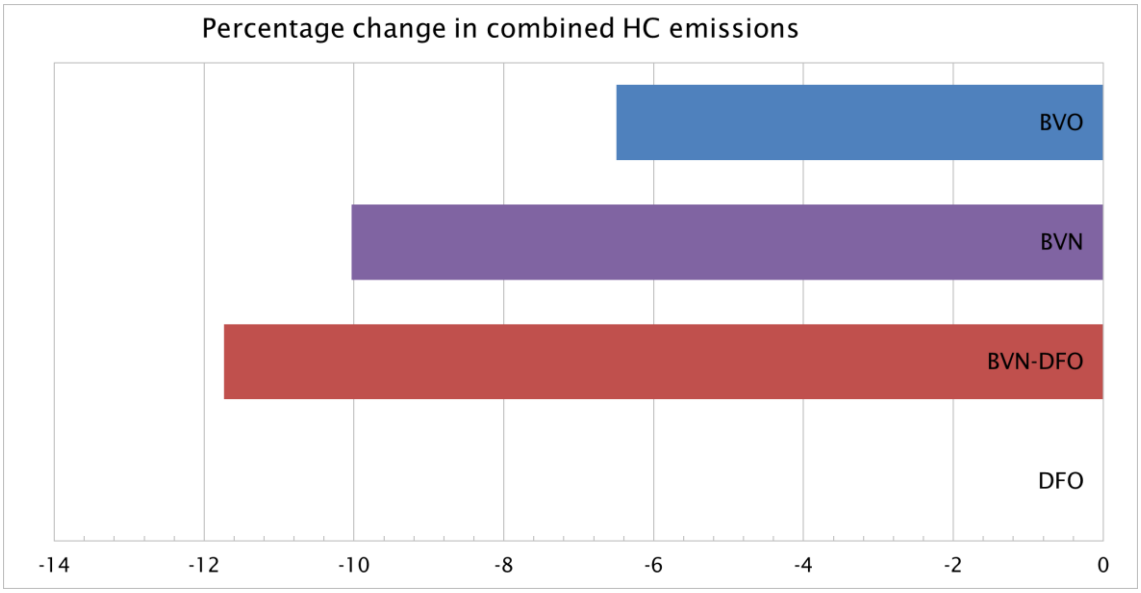


Figure 18. Percentage changes in the cycle-weighted brake specific HC emission for studied fuel options.

5.3.4 CO_2

Figure 19 shows wet exhaust CO_2 contents versus engine load at rated speed and Figure 20 for intermediate speed. At both speeds, CO_2 contents increased steadily with increasing engine load. The differences between fuels were quite small, especially at lower loads. At 10% load at rated speed results ranged from 2.2 to 2.3 vol-% and at full load from 7.4 to 7.7 vol-%. At 10% load at intermediate speed, results were 4.9-5.1 vol-% and at full load 8.3-8.5 vol-%.

If any trend could be observed, the CO_2 emissions seemed to be the lowest with BVO at most loads. Overall, the differences between the fuels were very minor and any significant conclusions could not be made. It should be noted, however, that the net GHG effect of renewable diesels BVO and BVN is much lower than that of fossil diesel.

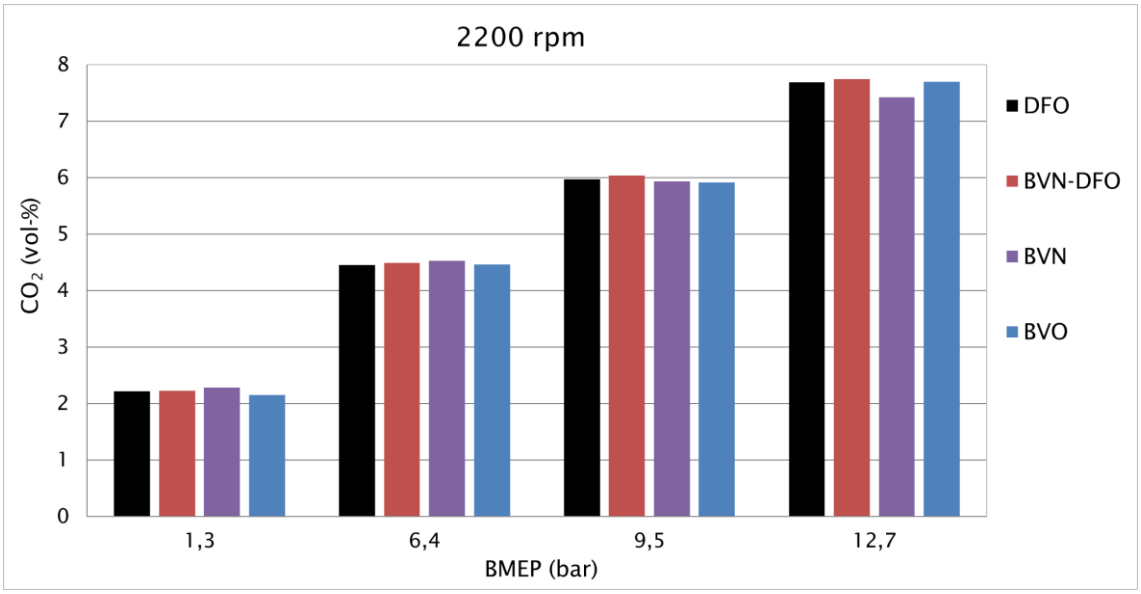


Figure 19. Exhaust CO_2 contents at load points at 2200 rpm.

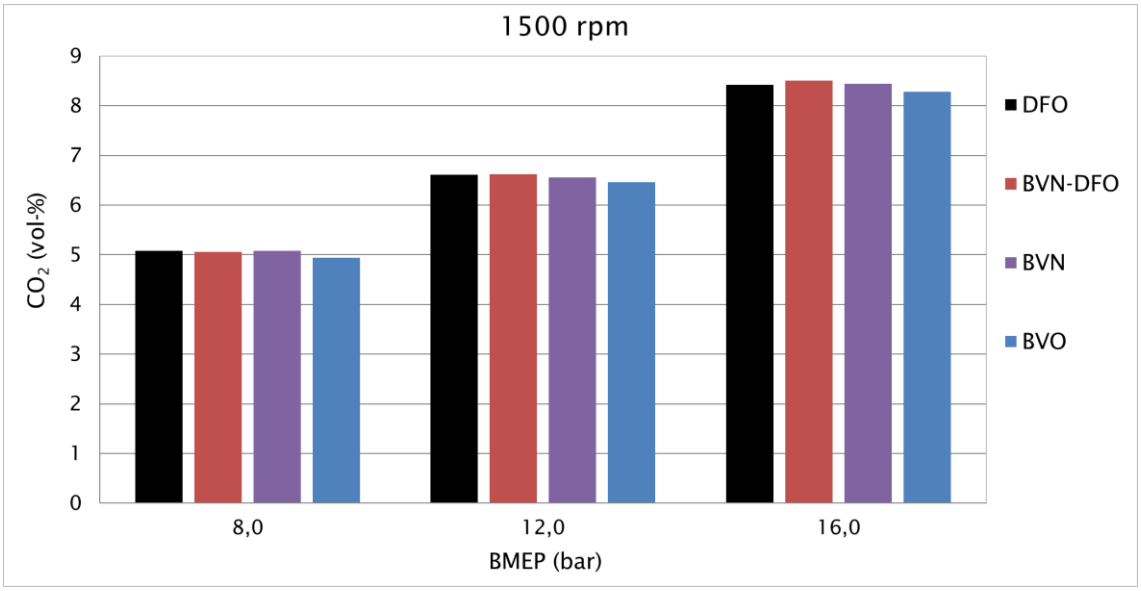


Figure 20. Exhaust CO_2 contents at load points at 1500 rpm.

5.3.5 Particles

Figures 21-24 show the exhaust particle size distributions at rated speed. At each load at rated speed, particle size distributions were identified to have bimodal shape. Accumulation mode peaks were higher than nucleation mode peaks. The total PN number comprises all particles recorded within the size range of 5.6 to 560 nm.

BVO generated the lowest accumulation mode PNs at all loads. At full and 75% loads the highest accumulation peaks were with BVN and at half and 10% loads with DFO. At load range of 10% to 75% loads the highest nucleation mode PNs were with BVN and at full load with BVO. In the load range of 10% to 75% BVN-DFO generated the lowest nucleation mode PNs and at the full load DFO.

Figures 25-27 show the exhaust particle size distributions at intermediate speed. At intermediate speed, the particle size distributions had bimodal shapes at higher loads. The total PN number comprises all particles recorded within the size range of 5.6 to 560 nm.

At full and 75% load the highest accumulation peaks were detected when BVN-DFO was used. At full load, the lowest nucleation PN were with DFO and at 75% load with BVN and BVO. At half load and low idle (Figure 28.) the exhaust did not contain as as many accumulation mode particles as at high loads. Nucleation mode peaks were much higher with DFO than with other fuels. At half load and on idle the lowest nucleation mode PN were with BVO

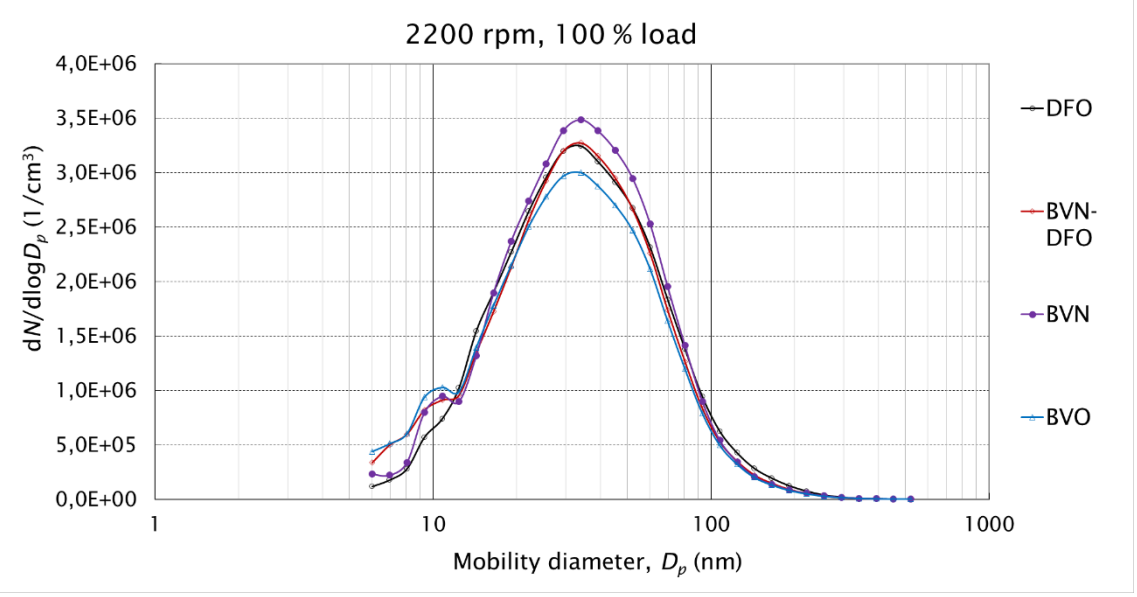


Figure 21. Exhaust particle size distributions at full load at 2200 rpm.

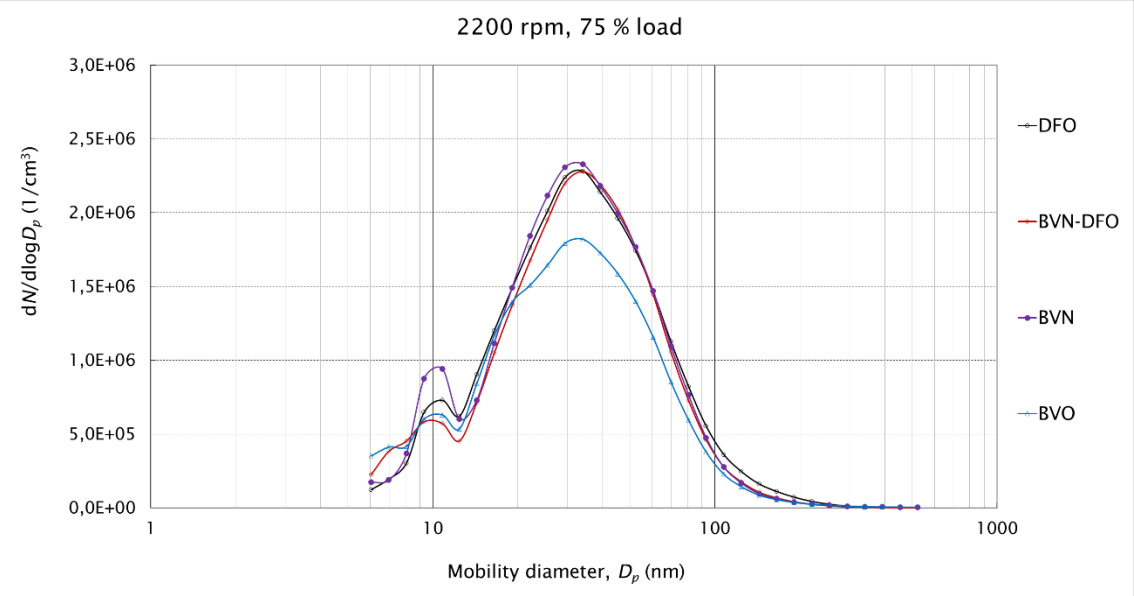


Figure 22. Exhaust particle size distributions at 75% load at 2200 rpm.

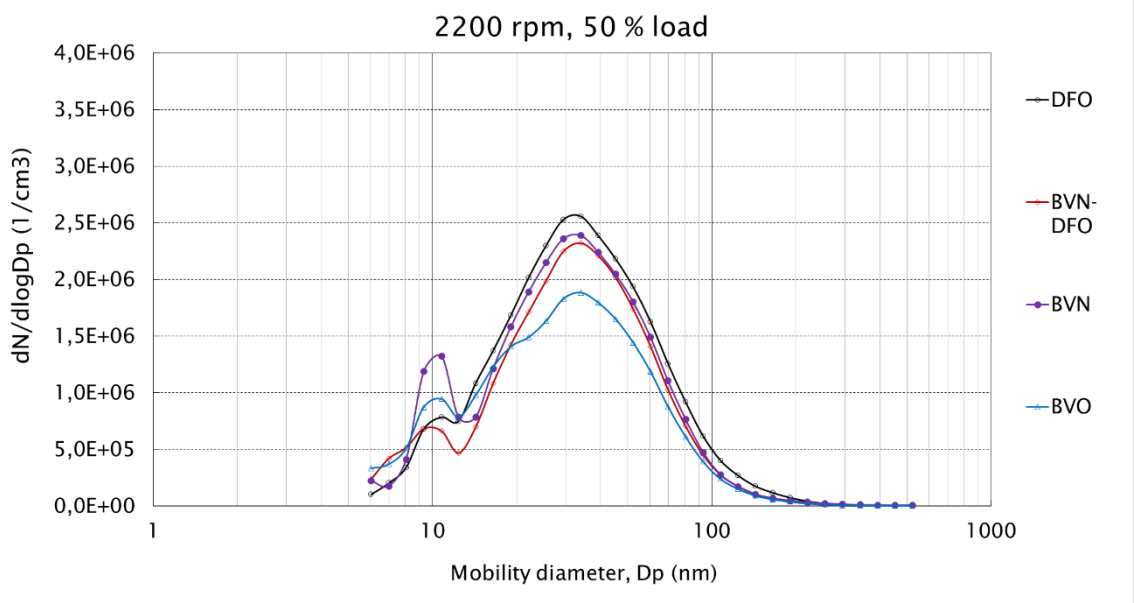


Figure 23. Exhaust particle size distributions at 50% load at 2200 rpm.

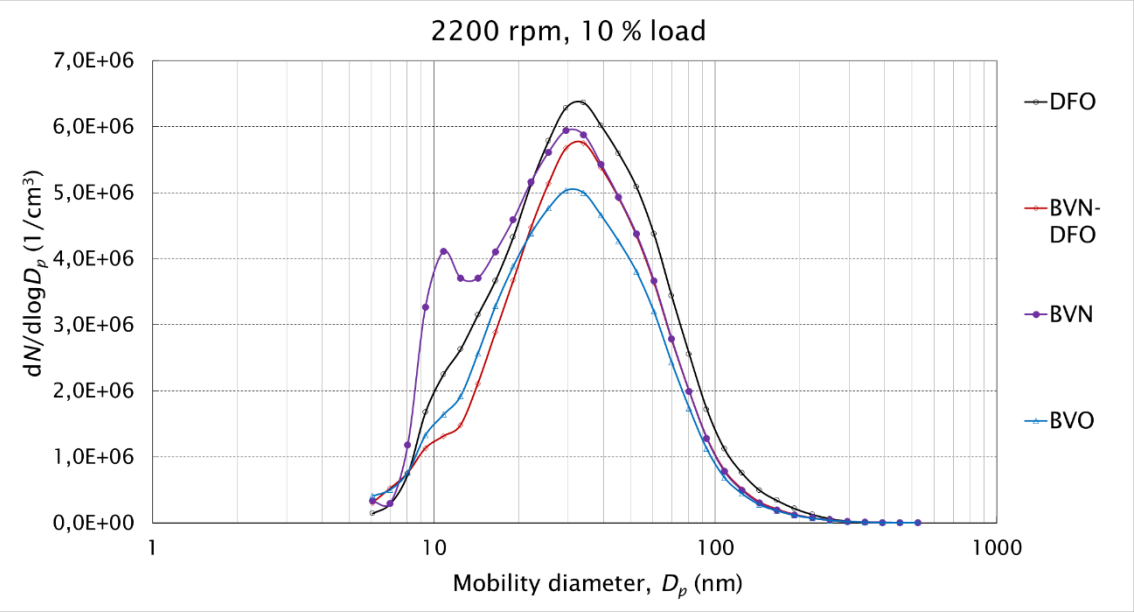


Figure 24. Exhaust particle size distributions at 10% load at 2200 rpm.

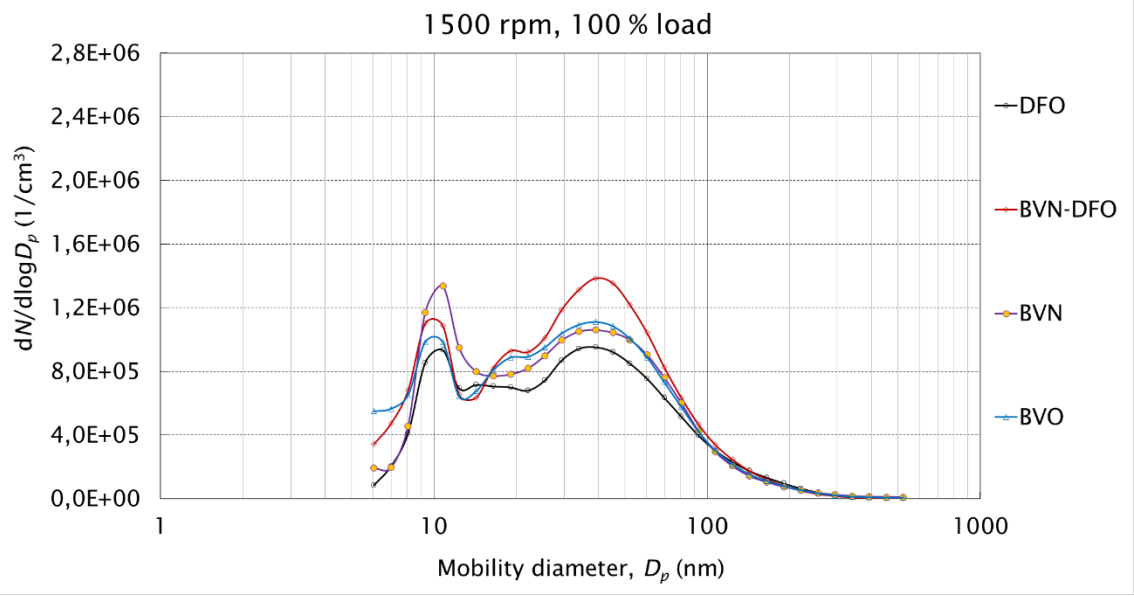


Figure 25. Exhaust particle size distributions at full load at 1500 rpm.

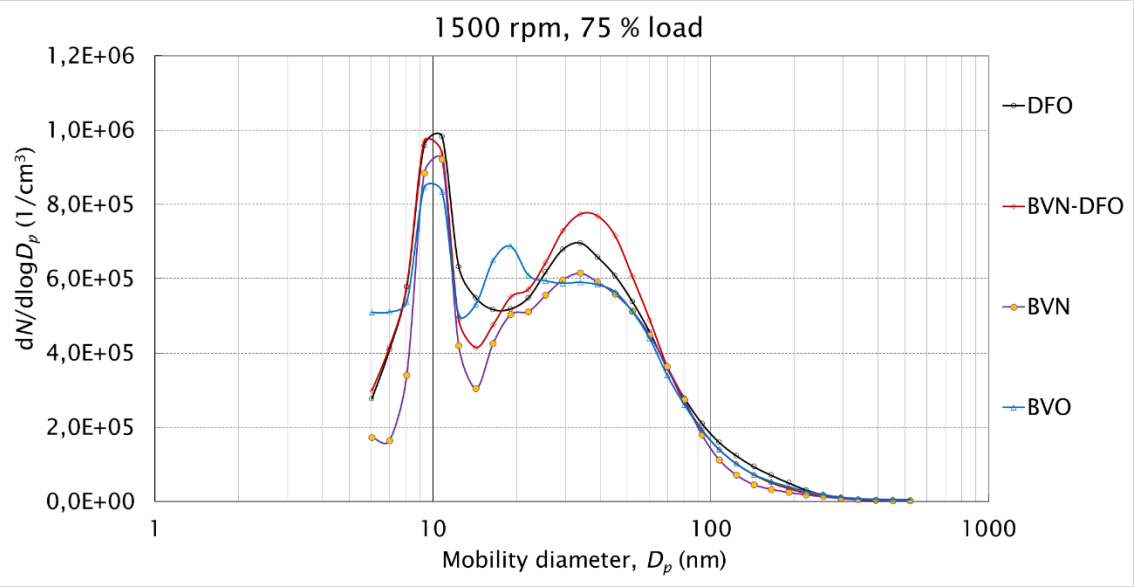


Figure 26. Exhaust particle size distributions at 75% load at 1500 rpm.

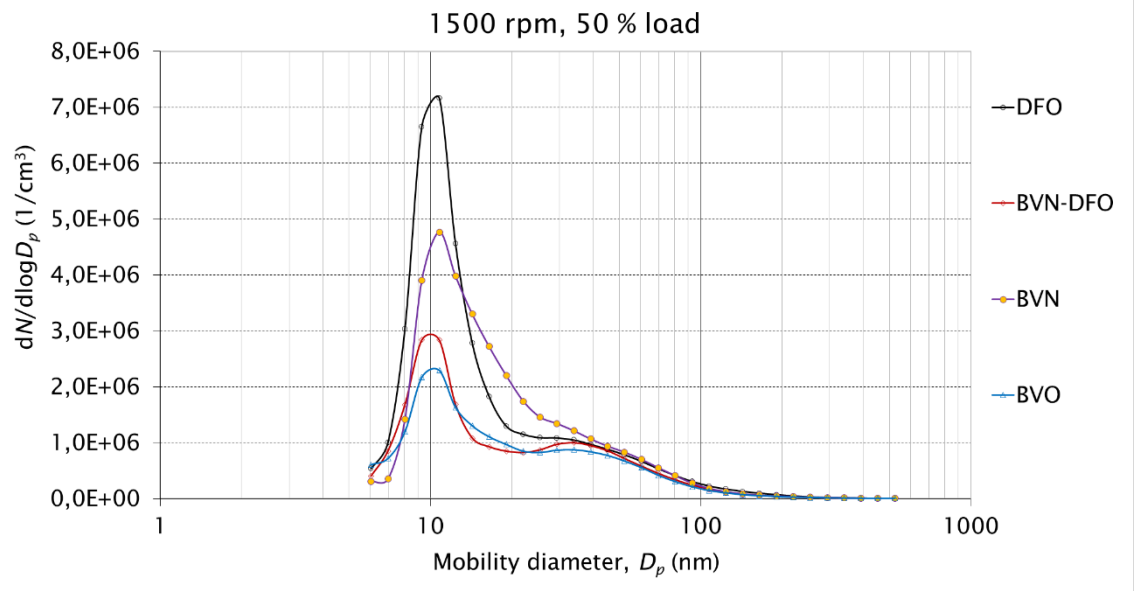


Figure 27. Exhaust particle size distributions at 50% load at 2200 rpm.

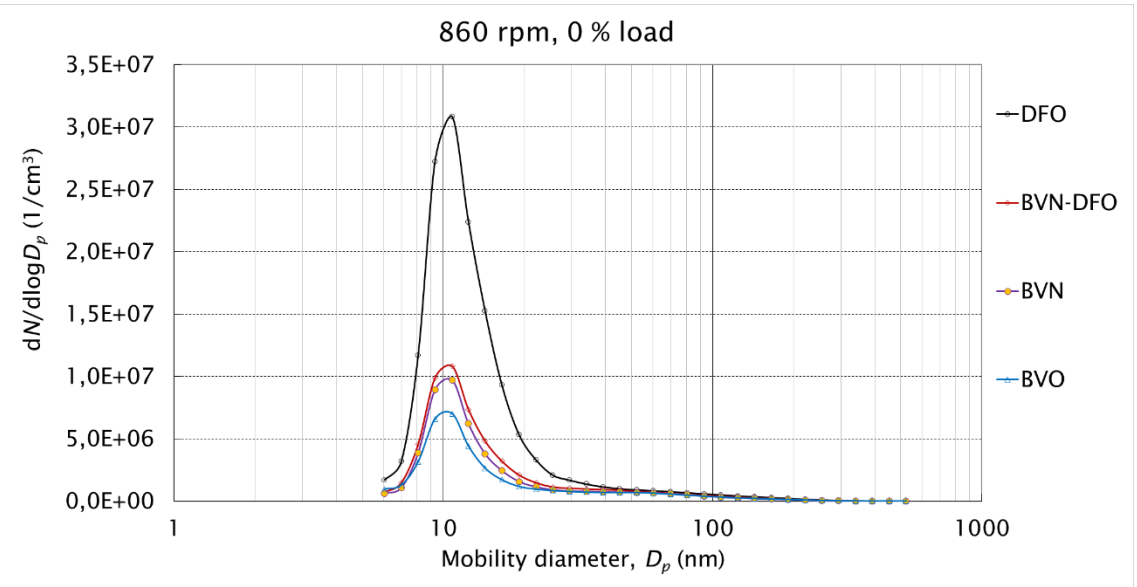


Figure 28. Exhaust particle size distributions at 50% load at 2200 rpm.

Figures 29 and 30 show the brake specific particle number versus engine load at rated speed rpm and Figure 31 at intermediate speed. At both speeds, the highest brake specific PN were at the lowest load. At medium loads PNs decreased and increased again slightly at full load. PNs were lower at intermediate speed than at rated speed.

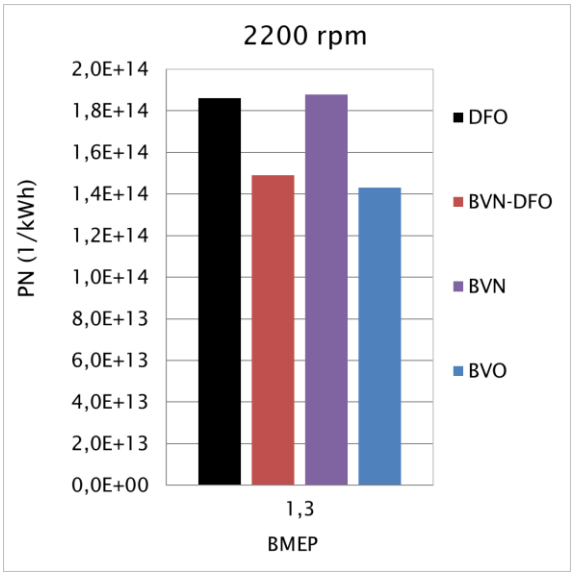


Figure 29. Total brake specific PN at 10 % load at 2200 rpm.

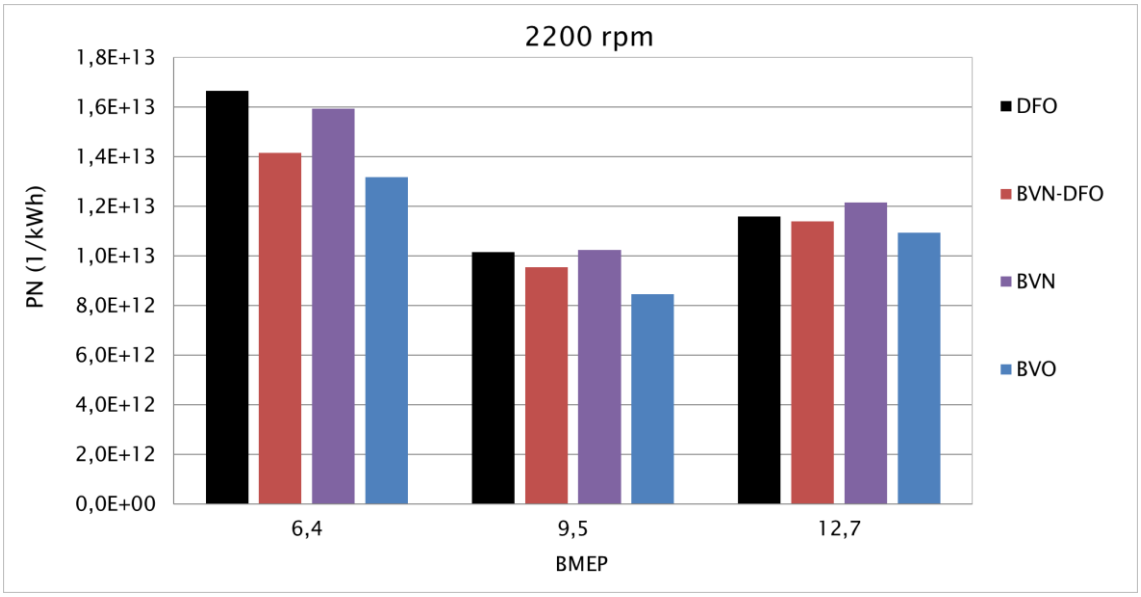


Figure 30. Total brake specific PN at 50-100% loads at 2200 rpm.

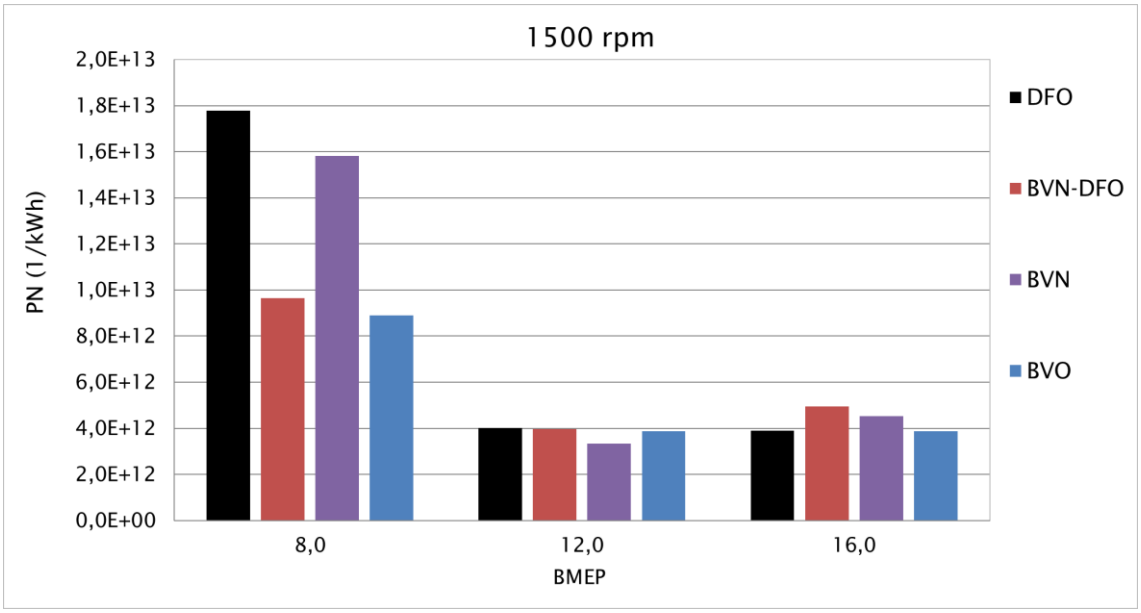


Figure 31. Total brake specific PN at 1500 rpm.

At all loads at rated speed BVO generated the lowest PNs. At 10%, 75% and full load BVN had the highest PNs. At half load PN were the highest with DFO. At intermediate speed PN were the highest with DFO at half load. At intermediate speed, there was not any clear trend detected in terms of PN.

Figure 32 shows weighted particle number over the cycle. Percentage reductions in PN are shown in Figure 33. BVO seemed to be the most favourable of all fuels achieving 26% reductions compared with DFO. With BVN-DFO PN emissions reduced by 20% and with BVN by 10%. The highest PN were when DFO was used.

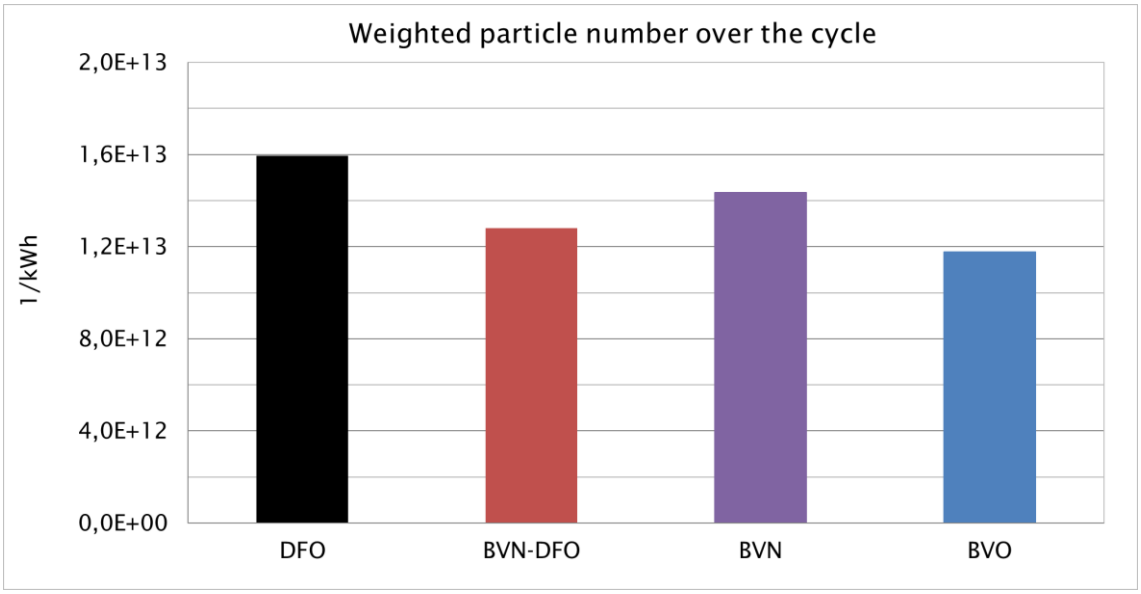


Figure 32. Weighted total PN over the cycle.

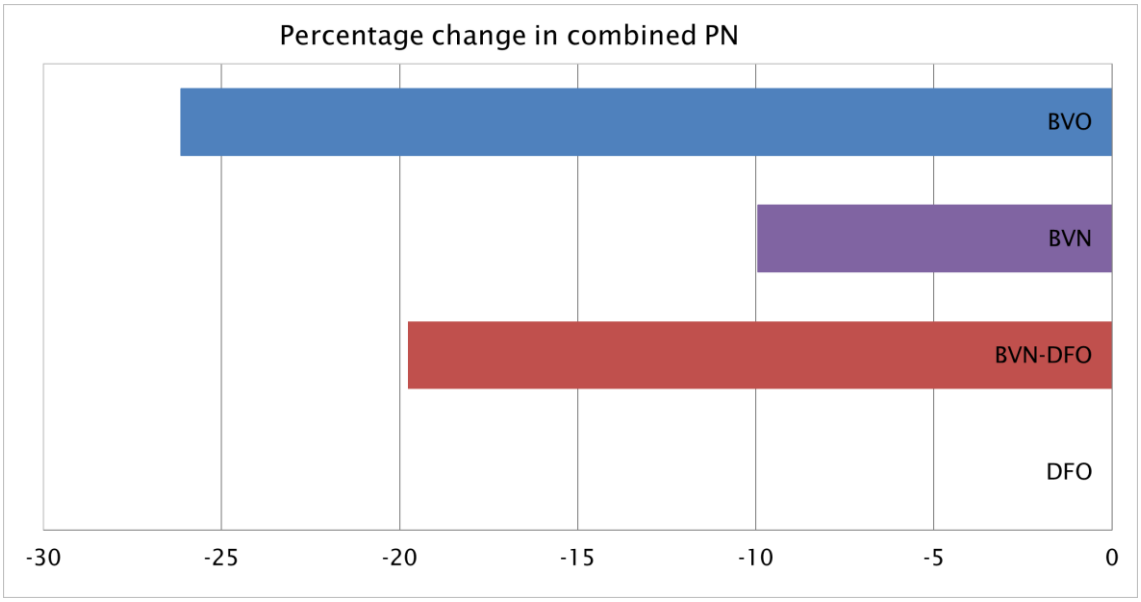


Figure 33. Relative changes in the weighted PN for different fuels compared with DFO.

6 Discussion

One of the reasons for the detected reductions in emissions was, most probably, the higher cetane numbers of renewable fuels and blends. High cetane number usually indicates that engine operates a high thermal efficiency and low fuel consumption which enables lower CO, HC and PN emissions. Combustion temperature and pressure in the cylinder also are lower when cetane number is high which leads lower NO_x emissions. Compared to fossil diesel, the higher cetane number of renewable diesels or their blends was caused presumably by their paraffinic content which was assumed to be relatively high.

Lower viscosity of HVOs eases mixture formation of fuel and air which further improves ignition quality resulting in lower emissions. HVOs have a lower distillation range than diesel fuel. Better evaporation behaviour of HVO enables improved mixture formation in the combustion chamber and it, most likely, reduces engine´s CO, HC and PN emissions.

Low PN emissions are also due to the low sulphur content in HVO. Sulphur oxidises to sulphur trioxide which converts to sulphur acids resulting higher PM emissions. Moreover, negligible aromatic content of renewable diesel can also explain the lower PN emissions compared to fossil diesel at idle and over the cycle.

7 Conclusions

In the present study, a common-rail non-road diesel engine was driven with three renewable diesel fuels and two renewable diesel fuel blends. Fossil diesel fuel was used as reference fuel. The main target was to study how renewable diesel affects the performance and exhaust emissions of the diesel engine. Measurements were conducted according to the C1 driving cycle of the ISO 8178 standard. The test engine had no exhaust aftertreatment systems and no engine or parameter modifications were made during the tests.

Based on measurements of this study, the following conclusions could be drawn:

- Compared with DFO, NO_x emissions over the cycle decreased when renewable diesel was used as neat or as a constituent of a blend. BVO seemed to be most beneficial with approximately 9% NO_x reductions. With BVN-DFO and BVN, the changes in NO_x remained quite low.
- Relative to DFO, the cycle-weighted CO emissions reduced with all renewable diesels and blends. The highest reductions, 9%, were achieved with BVN.
- The cycle-weighted HC emissions decreased when renewable diesel fuel or blend was used as neat or as a constituent of a blend instead of pure DFO. The most favourable fuel was BVN-DFO with approximately 12% HC reductions. BVN and BVO achieved 10% and 6% HC reductions, respectively.
- The cycle-weighted PN emission was highest with DFO and lowest with BVO achieving 26% reductions. DFO-BVN and BVN also managed well also with 20% and 10% reductions, respectively.
- At low idle, neat renewable diesels or their blends significantly reduced the nucleation mode PN compared to fossil diesel.

8 Summary

Diesel engines are popular especially in heavy duty-vehicles because of their high efficiency, durability, reliability and low-operating costs. However, despite of good qualities of diesel engines they play an important role in environmental pollution problem. Especially NOx and PM emissions are critical emissions of diesel engines.

Two of the European Union's climate and energy goals for 2030 are cutting at least 40% greenhouse gas emissions from 1990 levels and increase the share of renewable energy to 27% and make at least a 27% improvement in energy efficiency. The emission standard Stage V also sets tight limits for CO, HC, NOx, PM and PN emissions from diesel engines.

HVO fuel could be one of the solutions to lower emissions from diesel engines. HVO has similar chemical composition as fossil diesel, but it has benefits like higher cetane number and lower aromatic content compared to fossil diesel. Additionally, according to this study the emissions seem to be lower than fossil diesel. HVO can be derived from different vegetable oils and fats for example tall oil, algae oils, residues and wastes. With HVO there is also no need to modify the engine or existing fuel distribution infrastructure, so they could be used as direct replacement for fossil diesel in engine.

In this study the aim was to examine the effects of renewable diesels and renewable diesel blend on the performance and emissions of a non-road diesel engine. The engine was AGCO POWER 44 AWI, a turbocharged, intercooled (air-to-water) non-road diesel engine which had a common rail fuel injection system. The engine had no exhaust aftertreatment system. Studied fuels were renewable wood-based diesel fuels (BVO and BVN) and a renewable diesel fuel blend. DFO was used as a reference fuel. The fuel blend consisted of 50 vol.-% BVN and 50 vol.-% DFO. The measurements were conducted at eight load points which were selected according to the C1 driving cycle of the ISO 8178 standard.

Based on this study, NO_x, PN, CO and HC reductions were detected with all renewable fuels and the fuel blend over the NRSC. The highest reductions were in PN emission, between 10-16%. CO emission reduced by 2-9% and HC by 6-12%. In terms of NO_x, the highest reduction was 9% but otherwise reductions were quite low.

References

Aatola, H., Larmi, M., Sarjovaara, T. & Mikkonen, S. (2009). Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel Trade-off between NO_x, Particulate Emission, and Fuel Consumption of a Heavy-Duty Engine. SAE International Journal of Engines, 1(1), 1251-1262. https://doi.org/10.4271/2008-01-2500

Anthonykutty, J. M. (2015). Hydrotreating of tall oils on a sulfided NiMo catalyst for the production of base-chemicals in steam crackers. http://urn.fi/URN:ISBN:978-951-38-8240-2

Bauen, A., Gomez, I., OudeNijeweme, D., Paraschiv, M. (2011). Alternative Fuels, Expert group report. Directorate-General for Research and Innovation, Smart, Green and Integrated Transport. Retrieved from 6.4.2021 https://op.europa.eu/en/publication-detail/-/publication/22bbaffc-00bb-11e8-b8f5-01aa75ed71a1

Bhardwaj, O. P., Kolbeck, A. F., Kkoerfer, T. & Honkanen, M. (2013). Potential of Hydrogenated Vegetable Oil (HVO) in Future High Efficiency Combustion System. SAE International Journal of Fuels and Lubricants, 6(1), 157-169. https://doi.org/10.4271/2013-01-1677

Blom, J. (24.9.2020). Mäntyöljy voisi korvata fossiiliset muovit Suomessa – selluteollisuuden sivutuote taipuu mihin maaöljykin, mutta vastaako tarjonta kysyntää?. Yle Uutiset. Retrieved 6.4.2021 from https://yle.fi/uutiset/3-11557317

Creten, S. & Van Mullem, K. V. (2017). D5.9 Data collection and analysis of pilot test case for standard after-treatment configurations. Retrieved from https://www.prominent-iwt.eu/wp-content/uploads/2018/04/2017_12_13_PROMINENT_D5.9-Data-collection-and-analysis-of-pilot-test-cas.._.pdf

Dieselnet. (2001). Emission test cycles ISO 8178, Retrieved 6.4.2021 from https://dieselnet.com/standards/cycles/iso8178.php

DieselNet. (2002). Diesel Exhaust Particle Size. Retrieved 6.4.2021 from https://dieselnet.com/tech/dpm_size.php

Dieselnet. (2015). EU: Fuels: Automotive Diesel Fuel. Retrieved 6.4.2021 from https://dieselnet.com/standards/eu/fuel_automotive.php

DieselNet. (2016). Emission standards EU: Nonroad Engines. Retrieved 6.4.2021 from https://dieselnet.com/standards/eu/nonroad.php

Douvartzides, S. L., Charisiou, N. D., Papageridis, K. N., & Goula, M. A. (2019). Green diesel: Biomass feedstocks, production technologies, catalytic research, fuel properties and performance in compression ignition internal combustion engines. Energies (Basel), 12(5), 809-849. https://doi.org/10.3390/en12050809

Ecotech. (2010). Serinus 44 NO/NO2/NOx/NH3 Analyser. User Manual. Retrieved 7.4.2021 from https://www.ecotech.com/wp-content/uploads/2015/01/M010034-Serinus-44-NOx-NH3-User-Manual-Rev-1.0.pdf

Gasmet. (2020). Product Brochure DX4000. Retrieved 7.4.2021 from https://www.gasmet.com/wp-content/uploads/2018/01/Product-Prochure-DX4000-2020-web.pdf

Hajbabaei, M., Johnson, K. C., Okamoto, R. A., Mitchell, A., Pullman, M., & Durbin, T. D. (2012). Evaluation of the impacts of biodiesel and second generation biofuels on

NOx Emissions for CARB diesel fuels. Environmental Science & Technology, 46(16), 9163-9173. https://doi.org/10.1021/es300739r

Heikkilä, J., Happonen, M., Murtonen, T., Lehto, K., Sarjovaara, T., Larmi, M., Keskinen, J., & Virtanen, A. (2012). Study of miller timing on exhaust emissions of a hydrotreated vegetable oil (HVO)-fueled diesel engine. Informa UK Limited. https://doi.org/10.1080/10962247.2012.708383

Heuser, B., Vauhkonen, V., Mannonen, S., Rohs, H. & Kolbeck, A. (2013). Crude Tall Oil-Based Renewable Diesel as a Blending Component in Passenger Car Diesel Engines. SAE International Journal of Fuels and Lubricants, 6(3), 817-825. https://doi.org/10.4271/2013-01-2685

Heywood, J. B. (1988). Internal combustion engine fundamentals. McGraw-Hill Book Company.

Heywood, J. B. (2018). Internal combustion engine fundamentals. McGraw-Hill Education.

ICCT, 2016, European Stage V non-road emission standars, Retrieved 6.4.2021 from https://theicct.org/sites/default/files/publications/EU-Stage-V_policy%20update_ICCT_nov2016.pdf

ISO. (2020). 8178-4:2020 Reciprocating internal combustion engines — Exhaust emission measurement — Part 4: Steady-state and transient test cycles for different engine applications, Retrieved 6.4.2021 from https://www.iso.org/standard/79199.html

Jeihouni, Y., Pischinger, S., Ruhkamp, L. & Koerfer, T. (2011). Relationship between fuel properties and sensitivity analysis of non-aromatic and aromatic fuels used in a

single cylinder heavy duty diesel engine. SAE Technical Papers. https://doi.org/10.4271/2011-01-0333

J.U.M. Engineering. (2020). VE7 Heated FID Total Gaseous Organic Carbon Analyzer. Retrieved 7.4.2021 from https://www.jumfab.com/wp-content/uploads/2020/04/VE7-INT-12.pdf

Jääskeläinen, H. (2009). Biodiesel Standards & Properties. DieselNet. Retrieved 6.4.2021 from https://dieselnet.com/tech/fuel_biodiesel_std.php

Jääskeläinen, H. (2017). Fuel Property Testing: Low Temperature Operability. DieselNet. Retrieved 6.4.2021 from https://dieselnet.com/tech/fuel_diesel_lowtemp.php

Lapuerta, M., Villajos, M., Agudelo, J. R., & Boehman, A. L. (2011). Key properties and blending strategies of hydrotreated vegetable oil as biofuel for diesel engines. Fuel Processing Technology, 92(12), 2406-2411. https://doi.org/10.1016/j.fuproc.2011.09.003

Lee, R., & Kester, W. (2016). Complete Gas Sensor Circuit Using Nondispersive Infrared (NDIR). Analog dialogue. Retrieved 7.4.2021 from https://www.analog.com/media/en/analog-dialogue/volume-50/number-4/articles/complete-gas-sensor-circuit.pdf

Lehto, K., Antti Elonheimo, Häkkinen, K., Sarjovaara, T. & Larmi, M. (2012). Emission reduction using hydrotreated vegetable oil (HVO) with miller timing and EGR in diesel combustion. SAE International Journal of Fuels and Lubricants, 5(1), 218-224. https://doi.org/10.4271/2011-01-1955

Luke. (2020). Metsävarat. Suomen metsätilastot. Retrieved 6.4.2021 from https://stat.luke.fi/suomen-mets%C3%A4tilastot-2020-2020_fi

Majewski, W.A. & Jääskeläinen, H. (2019). Exhaust Particulate Matter. Dieselnet. Retrieved 6.4.2021 from https://dieselnet.com/tech/dpm.php

Majewski, W.A. & Jääskeläinen, H. (2020). What is Diesel Fuel. DieselNet. Retrieved 6.4.2021 from https://dieselnet.com/tech/fuel_diesel.php

Majewski, W. A. & Khair, M. K. (2006). Diesel emissions and their control. SAE International.

Metsäteollisuus ry. (2020). Suhdannekäänne painoi metsäteollisuuden tuotantomääriä viime vuonna; Sellun tuotannossa syntyi silti uusi Suomen ennätys: 8,32 miljoonaa tonnia. STT Info. Retrieved 6.4.2021 from https://www.sttinfo.fi/tiedote/suhdannekaanne-painoi-metsateollisuuden-tuotantomaaria-viime-vuonna-sellun-tuotannossa-syntyi-silti-uusi-suomen-ennatys-832-miljoonaa-tonnia?publisherId=3973&releaseId=69874779

Mollenhauer, K. & Tschöke, H. (2010). Handbook of Diesel Engines. https://doi.org/10.1007/978-3-540-89083-6

Neste Corporation. (2020). Neste Renewable Diesel Handbook Retrieved 6.4.2021 from https://www.neste.com/sites/default/files/attachments/neste_renewable_diesel_handbook.pdf

Niemi, S., Vauhkonen, V., Mannonen, S., Ovaska, T., Nilsson, O., Sirviö, K., Heikkilä, S., & Kiijärvi, J. (2016). Effects of wood-based renewable diesel fuel blends on the performance and emissions of a non-road diesel engine. Fuel (Guildford), 186, 1-10. https://doi.org/10.1016/j.fuel.2016.08.048

Nylund, N., Erkkilä, K., Ahtiainen, M., Murtonen, T., Saikkonen, P., Amberla, A., & Aatola, H. (2011). Optimized usage of NExBTL renewable diesel fuel. OPTIBIO. VTT Tiedotteita – Research Notes 2604. Retrieved 6.4.2021 from https://www.vttresearch.com/sites/default/files/pdf/tiedotteet/2011/T2604.pdf

Reşitoğlu, İ., Altinişik, K., & Keskin, A. (2015). The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technologies and Environmental Policy, 17(1), 15-27. https://doi.org/10.1007/s10098-014-0793-9

Siemens AG. (2018). Catalog sheet ULTRAMAT 6. Retrieved 7.4.2021 from https://cache.industry.siemens.com/dl/files/398/109765398/att_978556/v1/ultramat6_ap01_en.pdf

SFS. (2019a). SFS-EN 15940:2016 + A1:2018 + AC:2019:en. Automotive fuels. Paraffinic diesel fuel from synthesis or hydrotreatment. Requirements and test methods. SFS Standardien verkkokauppa. Retrieved 6.4.2021 from https://sales.sfs.fi/fi/index/tuotteet/SFS/CEN/ID2/1/753497.html.stx

SFS. (2019b). SFS-EN 14214:2013 + A2:2019:en. Liquid petroleum products. Fatty acid methyl esters (FAME) for use in diesel engines and heating applications. Requirements and test methods. SFS Standardien verkkokauppa. Retrieved 6.4.2021 from https://sales.sfs.fi/fi/index/tuotteet/SFS/CEN/ID2/1/745897.html.stx

Smagala, T. G., Christensen, E., Christison, K. M., Mohler, R. E., Gjersing, E., & McCormick, R. L. (2013). Hydrocarbon renewable and synthetic diesel fuel blendstocks: Composition and properties. Energy & Fuels, 27(1), 237-246. https://doi.org/10.1021/ef3012849

Sudalma, S., Purwanto, P. & Santoso, L. W. (2015). The Effect of SO2 and NO2 from Transportation and Stationary Emissions Sources to SO42− and NO3− in Rain Water in Semarang. Procedia environmental sciences, 23(C), 247-252. https://doi.org/10.1016/j.proenv.2015.01.037

TSI. (2016). Engine Exhaust Particle Sizer™ Spectrometer Model 3090. Retrieved 7.6.2021 from https://www.tsi.com/getmedia/a01ec52e-f39f-4312-8f9a-fded71631a69/3090_Engine_Exhaust_Particle_Sizer_A4_2980351_WEB?ext=.pdf

UPM. (2021). Producing advanced biofuels. Retrieved 6.4.2021 from https://www.upmbiofuels.com/about-upm-biofuels/production/

Vakkilainen, E. K. (2016). Steam Generation from Biomass: Construction and Design of Large Boilers, Elsevier Science & Technology. ProQuest Ebook Central. https://ebookcentral-proquest-com.proxy.uwasa.fi/lib/tritonia-ebooks/detail.action?docID=4696959.

Voiland, A., (1.6.2015). Fourteen years of carbon monoxide from MOPITT. NASA's Earth Observatory. Retrieved 6.4. 2021 from https://climate.nasa.gov/news/2291/fourteen-years-of-carbon-monoxide-from-mopitt/

Winther, M., & Dore, C. (2019). EMEP/EEA air pollutant emission inventory guidebook. Retrieved 6.4.2021 from https://www.eea.europa.eu/ds_resolveuid/6H3DTV1K4Z

World Health Organization. (2005). Air quality Guidelines, Global Update 2005. Retrieved 6.4.2021 from https://apps.who.int/iris/bitstream/handle/10665/107823/9289021926_eng.pdf?sequence=2&isAllowed=y

World Health Organization. (2013). Health effects of particulate matter. Policy implications for countries in eastern Europe Caucasus and central Asia. Retrieved 6.4.2021 from https://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf

Zeman, P., Hönig, V., Kotek, M., Táborský, J., Obergruber, M., Mařík, J., Hartová, V., & Pechout, M. (2019). Hydrotreated vegetable oil as a fuel from waste materials. Catalysts, 9(4), 337. https://doi.org/10.3390/catal9040337